A PROBABILISTIC ASSESSMENT OF FAILURE FOR AIR FORCE BUILDING SYSTEMS

THESIS

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Abstract

Deteriorating and failing federal facilities represent a cost to leaders and organizations as they attempt to manage and maintain these assets. Currently the Air Force employs the BUILDER™ Sustainment Management System to predict the reliability of building components. At different system levels, however, the probabilities of failure are not predicted. The purpose of this research is to provide probabilistic models which predict the probability of failure at the system level of a building's infrastructure hierarchy. This research investigated the plumbing, HVAC, fire protection, and electrical systems.

Probabilistic models were created for these systems by using fault trees with fuzzy logic on the basis of risk by weighting the probabilities of failure by the consequences of failure. This thesis then validated each of the models using real-world Air Force work order data. Through contingency analysis, it was found that the current BUILDER™ condition index model possessed no predictive ability due to the resulting p-value of 1.00; the probabilistic models possessed much more predictive ability with a resulting p-value of 0.12. The probabilistic models are statistically shown to be a significant improvement over the current condition index model; these models lead to improved decision making for infrastructure assets.

Acknowledgments

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I would also like to thank my sponsors, Mr. Mike Grussing and Mr. Lance Marrano, from the US Army Engineer Research and Development Center Construction Engineering Research Laboratory for your selflessness in providing support and time in this effort. By providing me with the data and the answers to a multitude of my questions, it made this research possible, for which I am truly grateful. Lastly, I want to thank Mr. Art Uhlig, the ACES/IWIMS Program Manager for providing civil engineer work order data which made the validation of my research possible.

Stephanie L. Alley

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A PROBABILISTIC ASSESSMENT OF FAILURE FOR AIR FORCE BUILDING SYSTEMS

I. Introduction

"Another flaw in the human character is that everybody wants to build and nobody wants to do maintenance." — Kurt Vonnegut, Jr.

Chapter Overview

The main purpose of this chapter is to introduce the focus of this research effort and associated background information. The chapter defines the problem statement and establishes the research objectives. In the background section, the chapter introduces the building infrastructure hierarchy and continues with the definitions of risk, risk assessment, and failure. The chapter concludes with a summation of the chapter structure and intent of effort.

Background

The United States Air Force currently owns and maintains a portfolio of buildings and structures numbering over 135,000 with a plant replacement value of $247 billion (DUSD(I&E), 2013:8). Each of these buildings was built to support a number of strategic missions for the Air Force including supply, administration, maintenance, production, operation, and training. Due to a variety of physical factors, these buildings age and degrade over time and their ability to support the missions for which they were built also degrades with time (Grussing et al., 2014).

Buildings are comprised of systems and components crossing civil, mechanical, and electrical construction disciplines (Grussing & Marrano, 2007). Examples of building systems include: foundation, roofing, interior construction, plumbing, and electrical. A system can be segmented into its individual components, and each component is further divided into one or more units called component-sections or sections, as shown in Figure 1.

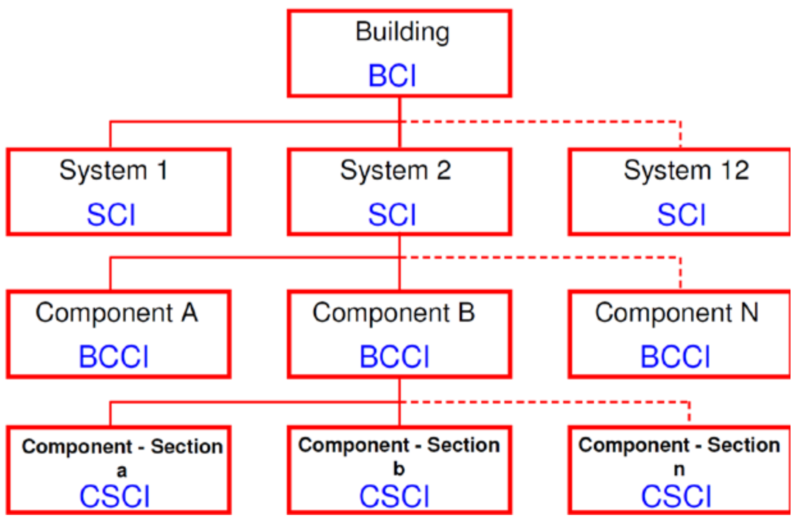


Figure 1: Building Infrastructure Hierarchy (Uzarski & Grussing, 2006)

To paraphrase Grussing and Marrano (2007: 550), each section works interdependently with other sections to support the functions of an efficiently operating building. As a physical asset, these sections age and deteriorate over time, ultimately adversely affecting performance and reliability of the building. Age and deterioration introduce risk to the building infrastructure, more specifically the risk of failure of the sections.

Risk

Risk is defined as "the chance of something happening that will have an impact on objectives" (Standards Australia/Standards New Zealand, 2004:3). Risk can further be defined as a function of both likelihood and a measure of consequence (Standards Australia/Standards New Zealand, 2004:49). The likelihood is also known as the probability or frequency, and it is a measure of the chance of the consequence occurring. Likelihood can be expressed either qualitatively or quantitatively, but it is generally expressed quantitatively as a number between 0 and 1. The consequence can also be thought of as the impact of risks which might jeopardize the objectives. As with likelihood, consequence can also be expressed either qualitatively or quantitatively.

As stated earlier, risk can be defined as a function of both likelihood and a measure of consequence (Standards Australia/Standards New Zealand, 2004:49). From this definition, risk can be shown in Equation 1.

$$\text{Risk} = f\ (\text{Likelihood, Consequence}) \tag{1}$$

This research then assumes that the level of risk is proportional to each of its factors, likelihood or consequence, and therefore the risk function is essentially a product (Standards Australia/ Standards New Zealand, 2004:49). This can be shown mathematically in Equation 2.

$$\text{Risk} = \text{Likelihood} \times \text{Consequence} \tag{2}$$

Risk Assessment

According to Standards Australia/Standards New Zealand (2004), risk assessment is about developing an understanding of the risk within the context of infrastrucuture management. Risk assessment sets out to quantify the likelihood and severity of each specific threat and the consequences should that threat occur (Labi, 2013). This aims to answer questions relating to how likely it is that something will go wrong, and what will happen if it does go wrong (Labi, 2013). In the case of this research, the negative impacts determined in the risk assessment will be termed as failure.

Failure

For every system or component, failure will eventually occur; although predicting when is difficult. Failure is defined as "an event or state of a system in which the system or any of its components does not perform as intended" (Wasson, 2006). This type of failure is the catastrophic failure, but failure can also be thought of as the approach to failure, also known as degradation. The approach to failure is the decrease in condition that occurs over time due to aging with or without normal maintenance (Bucholz, 2014).

History of Air Force Asset Management

To aid in managing infrastructure risk, Air Force civil engineering began transitioning to an asset management culture in 2007. According to Maj Gen (retired) Eulberg, "asset management can be defined as using systematic and integrated processes to manage natural and built assets and their associated performance, risk, and expenditures over their life cycles to support missions and organizational goals" (Eulberg, 2007:2). Furthermore, Eulberg stated that asset managers will be expected to apply a disciplined, deliberate approach to managing our asset portfolio in a more holistic and proactive manner, and will provide strategic direction by asking several important questions:

- What assets do we need?
- What assets do we have?
- What's the resulting capability gap?
- What are the options to optimize these assets?

The proposed way forward was through creating and reengineering processes, developing asset management tools such as robust training program, and ensuring that the entire management process is supported by a powerful information technology (IT) system. One IT system currently being utilized by Air Force asset managers is the system.

BUILDER™

Background

The BUILDER™ Sustainment Management System (SMS) is a web-based sofware application developed by the U.S. Army's Engineer Research and Development Center's (ERDC) Construction Engineering Research Laboratory (CERL) to help civil engineers, technicians, and managers decide when, where, and how to best maintain building infrastructure (BUILDER™, 2013). BUILDER™ functions as an integrated maintenance and repair (M&R) requirements prediction model and decision support tool for facility managers (Ottoman et al., 1999:79). According to Ottoman et al., "requirements are modeled through a process of inventory, inspection, condition assessment, deterioration modeling, condition prediction, and M&R planning." These elements are integrated together into the BUILDER™ SMS application.

Inventory of the facility is the first step in BUILDER™. To paraphrase Ottoman et al. (1999:80), inventory information is loaded into the BUILDER™ database to establish the building/system/component/component-section/subcomponent hierarchy, guiding the inspection effort, component condition prediction, and M&R planning and budgeting. BUILDER™ uses the UNIFORMAT II to classify the inventory levels. The next step is the inspection and condition assessment process. The purpose of the condition assessment is to capture the state of an asset to inform future investment decisions and to reduce risk (USACE, 2014b).

UNIFORMAT II

The UNIFORMAT II originated from a report published by the National Institute of Standards and Technology (NIST), which recommended a classification of building elements (Charette & Marshall, 1999:iii). Charette and Marshall continue that the American Society for Testing and Materials (ASTM) used the report as the basis for a standard classification of building and site-related elements, as the UNIFORMAT II was developed through an industry/government consensus process. BUILDER™ utilizes levels 2 and 3 of the UNIFORMAT II approach. Level 2 in UNIFORMAT II represents the group elements which corresponds to the system level in BUILDER™. Additionally, level 3 in UNIFORMAT II represents the individual elements which corresponds to the component level in BUILDER™. The UNIFORMAT II building elements in levels 1, 2, and 3 can be found in Appendix A.

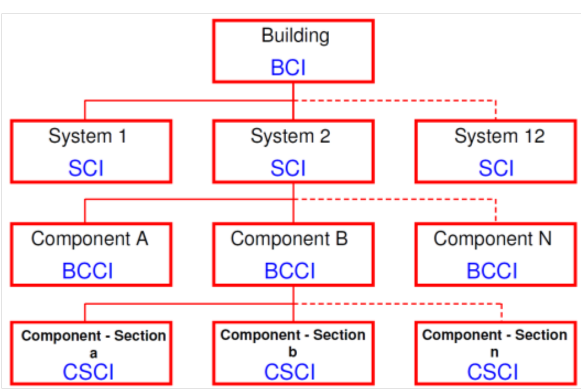
Condition Index

The condition of a facility is measured through the Condition Index (CI) which is an ordinal scale from 0 (failed) to 100 (defect free). In the condition index hierarchy, the

Component-Section Condition Index (CSCI) is the fundamental condition metric. The CSCI captures the building inspector's assessment at the lowest, most detailed level of the building hierarchy. Inspection occurs at this level and nowhere else in the hierarchy. From the CSCI, all subsequent building hierarchy condition indexes are derived.

The CSCI is "rolled up" to the Building Component Condition Index (BCCI), the System Condition Index (SCI) and finally the Building Condition Index (BCI). The BUILDER EMS Version 3 User Manual (USACE ERDC-CERL, 2007:89-90), outlines how CSCI's are rolled-up to compute the CI of the building (BCI) as a whole. Below are brief descriptions of each derived index and Figure 2 depicts the CI hierarchy and these weighted formulas:

- **Building CI (BCI).** For each building, the BCI is computed by taking the average of its system CI's weighted by replacement cost (CRV)
- **System CI (SCI).** For each system, the SCI is computed by taking the average of its component CI's weighted by replacement cost (CRV)
- **Component CI (BCCI).** For each component, the BCCI is computed by taking the average of its section CI's weighted by replacement cost (CRV)



$$BCI = \frac{\sum[SCI \times Individual\ System\ CRV]}{\sum Systems\ CRV}$$

$$SCI = \frac{\sum[BCCI \times Individual\ Component\ CRV]}{\sum Components\ CRV}$$

$$BCCI = \frac{\sum[CSCI \times Individual\ Section\ CRV]}{\sum Sections\ CRV}$$

Figure 2: Condition Index Hierarchy and Weighted Formulas (Adapted from Uzarski & Grussing, 2007)

Problem Statement

Deteriorating and failing federal facilities can pose numerous risks to an organization, especially when the risk is failure. The Condition Index is used to predict the reliability at various hierarchy levels. Furthermore, the current methodology rolls up the CI using the replacement value (i.e., cost to replace) as a metric. At this time though, BUILDER^{TM} can only compute CIs at the various hierarchies of a building system. However, CI is not equivalent to the reliability of a building. Therefore, BUILDER^{TM} cannot compute the probability of failure at the component-section level, component level, nor the system level.

Research Objectives and Investigative Questions

This research sets out to improve on the current BUILDER risk model starting at the component-section level and building up to the system level. The results of this assessment will be determined by answering the following investigative questions:

1. What are the probabilities of failure of the component-sections comprising the system and/or building?

2. What are the consequences of failure of the component-sections comprising the system and/or building?

3. If a system fails, what is the probability that the failure can be attributed to a specific component-section?

4. Can a model be created to predict the probability of failure at the component-section, component, and system levels?

Conducting a risk assessment at all levels of the building infrastructure hierarchy provides the framework for decision-making. Obtaining better insight of building performance will aid decision-makers by indicating the optimal time to maintain and repair specific building systems, components, and component-sections. Thus, this research aids in the development of more strategic approaches for investing in facilities maintenance and repair to achieve beneficial outcomes and mitigate risks.

Research Approach and Assumptions

This research calculates the likelihood of failure using the statistical Weibull failure model. Weibull models estimate the probability of failure and are widely used to estimate the weak link in a system (National Research Council, 2012:52). In this research, instead of having the consequence of failure relate to the impact, the consequence will be represented by importance values. Such importance values include the Component Importance Index (CII) and subcomponent weight factors. The CII is a measure that conveys the relative importance of a building component asset, while subcomponent weight factors indicate the relative importance of each subcomponent in terms of the cost to replace and the importance or criticality to the overall component (USACE, 2014a).

The statistical failure model will be validated using real-world failure data. These data will be obtained from previous Civil Engineering Work Orders (WOs). The WOs will be descriptive enough to document the building system that has failed and is in need of repair. Then, the service life of the component-sections will be found using BUILDER™ data, which can be input into the model in order to compute the probability of failure for the building system in question. Lastly, the probability of failure based on the service lives of the component-sections will be compared to the System Condition Index produced by BUILDER^{TM}.

Overview

This thesis document follows the traditional five-chapter format. Chapter II consists of an extensive literature review of risk-based investment and prioritization approaches and facility performance prediction. Chapter III presents the methodology employed in this research which is primarily the concept of fault trees using fuzzy logic. Chapter IV includes the analysis and results from the probabilistic risk assessment as well as validation of the probabilistic model. The final chapter, Chapter V of this research effort, provides the discussion and conclusions, recommendations, and suggestions for follow-on research.

II. Literature Review

Chapter Overview

This chapter provides a foundation for understanding the central topics of this research based on existing literature. First, this research effort uses data inherent to BUILDER^{TM}; therefore, this chapter builds on the BUILDER^{TM} concepts such as the Condition Index (CI) previously laid out. Next, in an effort to predict facility performance, the relationship between the condition and service life is discussed. This chapter provides a quantitative definition of failure. To aid this initiative, the failure model which uses the Weibull cumulative probability distribution function is discussed. Finally, the concept of fault trees using fuzzy logic is introduced.

Facility Performance Prediction

According to the National Research Council (2004:67), "performance prediction is based on an understanding of the facility's life cycle and deterioration over time." This basis becomes especially difficult with the realization that a facility is not one single entity; it is made up of a series of systems, components, and component-sections. These component-sections work interdependently with other component-sections to support the functions of an efficiently operating building (Grussing et al., 2006). However, these components can and most likely will all have different service lives. For certain component-sections, such as the slab on grade foundation, the service life will correspond with the life of the facility; other component-sections, such as an air-handling unit, have a service life much shorter than the total life of the facility.

Service Life

According to Grussing et al. (2006), the lifespan of a component-section is rarely known exactly, and the actual service life depends greatly on local environmental factors, use and abuse, and levels of routine maintenance accomplished. Local environmental factors can include the region in which the facility is located because climate can greatly impact the HVAC system's ability to handle harsh climates. While component-sections are rarely installed just to be misused or abused, abuse happens when the mission, and therefore the load requirement, is not known in advance. Grussing et al. (2006:20) state that "periodic repair or replacement of the various component-sections is needed to restore condition and performance capabilities."

The repair or replacement for building components varies. Table 1 contains a listing of the mean lives of building systems. To calculate these service life figures, BUILDER™ has built-in Service Life Books that contain component-section level service life information. These values for each of the service lives are obtained from industry sources such as R.S. Means, Building Owners and Managers Association (BOMA), and American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), and can be edited to follow real-world data. The Air Force utilizes its own separate Service Life Book in the BUILDER™ program.

Table 1: Mean Lifecycle of Building Systems (Adapted from Ottoman, 1997)

Building Component	**Average Life**
Foundations, floors, structural walls, roof structures, stairs	75 years
Roofing (including coverings, insulation, and specialties)	20 years
Interior walls and doors, windows	50 years
Wall and floor finishes, paint, wall coverings, and carpeting	7 years
Ceiling finishes	20 years
Elevators	40 years
Fire protection equipment	50 years
HVAC	20 years
Plumbing (water and sewer)	40 years
Electrical (including wiring, switches, receptacles, and fixtures)	30 years
Special equipment (including appliances, bookcases, and cabinetry)	25 years

The estimated service life of a component-section can indicate two useful pieces of information needed for good M&R planning. First, it indicates how long that component-section is expected to last in the facility so that engineers can plan for its eventual replacement. Second, it can indicate the most efficient point when corrective action should be considered or performed. The efficient point is the point in time when an M&R corrective action returns the greatest increase in condition index. According to Grussing et al. (2006), this efficient point is rarely near or after the failure state has occurred. For many component-sections, repairs performed early in the lifecycle, and well before failure, can extend the component-section’s life and avert expensive damage caused by accelerated degradation (Grussing et al., 2006).

Condition Assessments

As previously mentioned in Chapter I, the purpose of the condition assessment is to capture the condition state of an asset in order to inform future investment decisions and to reduce risk (USACE, 2014b). The objective of condition assessments is to measure the "health" of specific components, systems, and buildings (USACE, 2014a). Additional objectives include the formation of a basis for both determining rates of deterioriation and predicting the condition of components, systems, and buildings (USACE, 2014a). BUILDER™ utilizes two different methods of condition assessments: direct rating and distress survey.

Direct Rating

The direct condition rating procedure is a less precise, but faster method for performing a condition survey (USACE ERDC-CERL, 2013). It involves visually inspecting each component-section, evaluating the entire component-section against a set of rating criteria, and selecting the appropriate rating (USACE ERDC-CERL, 2013). These rating criteria consist of the three broad categories of Red, Amber, and Green, with each rating category being divided into three classes denoted by high (+), low (-), and middle. Table 2 shows the direct rating definitions. If the component-section is large and/or discontinuous, sampling is permitted (Uzarski et al., 2007).

According to USACE ERDC-CERL (2007), for direct ratings, the color rating chosen directly corresponds to a deduct value for the component-section. The Component-Section Condition Index (CSCI) can then be easily computed using this deduct value. Furthermore, if sampling is used for the component-section, a sample unit Condition Index will be computed at each sample location and aggregated into a CSCI by computing the average of the representative samples weighted by size (USACE ERDC-CERL, 2007).

Table 2: Direct Condition Rating Definitions (Adapted from USACE ERDC-CERL, 2013:30)

Rating	Rating Definition
Green (+)	Entire component-section or component-section sample free of observable or known distress.
Green	No component-section or sample serviceability or reliability reduction. Some, but not all, minor (non-critical) subcomponents may suffer from slight degradation or few major (critical) subcomponents may suffer from slight degradation.
Green (-)	Slight or no serviceability or reliability reduction overall to the component-section or sample. Some, but not all, minor (non-critical) subcomponents may suffer from minor degradation or more than one major (critical) subcomponent may suffer from slight degradation.
Amber (+)	Component-section or sample serviceability or reliability is degraded, but adequate. A very few, major (critical) subcomponents may suffer from moderate deterioration with perhaps a few minor (non-critical) subcomponents suffering from severe deterioration.
Amber	Component-section or sample serviceability or reliability is definitely impaired. Some, but not a majority of major (critical) subcomponents may suffer from moderate deterioration with perhaps many minor (non-critical) subcomponents suffering from severe deterioration.
Amber (-)	Component-section or sample has significant serviceability or reliability loss. Most subcomponents may suffer from moderate degradation or a few major (critical) subcomponents may suffer from severe degradation.
Red (+)	Significant serviceability or reliability reduction in component–section or sample. A majority of subcomponents are severely degraded and others may have varying degrees of degradation.
Red	Severe serviceability or reliability reduction to the component-section or sample such that it is barely able to perform. Most subcomponents are severely degraded.
Red (-)	Overall component-section degradation is total. Few, if any, subcomponents salvageable. Complete loss of component-section or sample serviceability.

Distress Survey

The distress survey method of condition assessments is a more intensive method of inspection where distresses are selected from a pre-defined list of choices. Severity is entered as high, medium, or low, along with a quantity for each subcomponent comprising a component-section (USACE, 2014b). The quantity is measured as either a specific distress quantity (e.g., 20 LF) or a density estimation within a predefined range (e.g., 1-5%). There are 23 distinct distress types such as animal damage, blisters, inoperable, and vibration. An example subcomponent distress model can be found in Figure 3. These distresses and quantities determine the deduct values to determine the Condition Index for each subcomponent (USACE, 2014a).

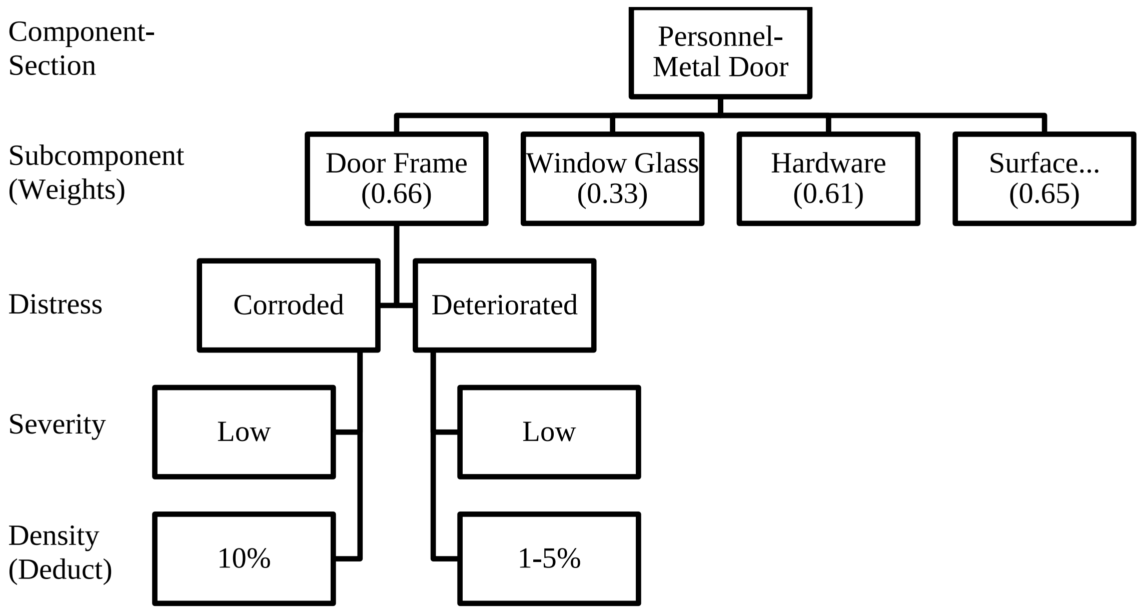


Figure 3: Example Subcomponent Distress Model (Adapted from USACE, 2014a)

Lifecycle Condition Trend

The relationship between the service life and the condition of a component-section produces a performance curve also known as a lifecycle curve. This lifecycle curve plots the relationship between the service life of the component-section (in years) and the condition of the component-section in terms of its Condition Index. An example of this curve can be seen in Figure 4. Along with having a finite service life, Uzarski and Grussing (2006) state that each component-section has a maintenance window where repair work actions can be performed to correct accumulated degradation and restore some lost condition.

Additionally shown in Figure 4, the remaining service life (RSL) is the difference between the current age and expected service life. The remaining maintenance life (RML) is the difference between the current age and some scheduled beneficial maintenance or repair action. As the Component-Section Condition Index (CSCI) degrades, the component-section approaches the "sweet spot" for maintenance and repair. The "sweet spot" is a narrow range of CSCI values that represent the economically optimum condition where maintenance and repair work should be performed, theoretically at a CSCI range of 70-80 (Uzarski & Grussing, 2006).

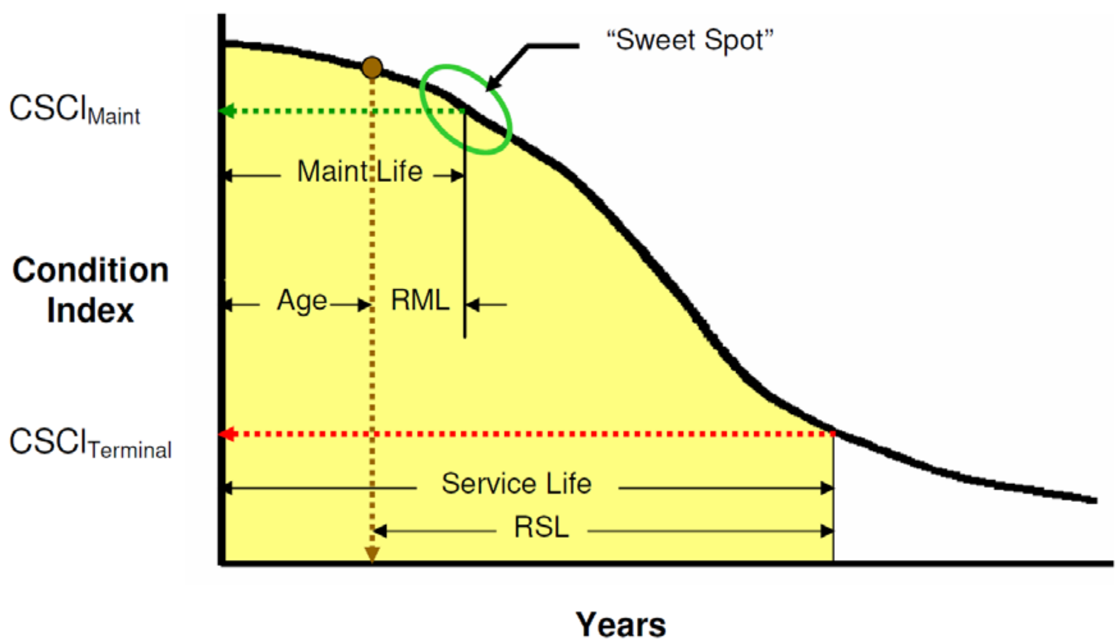


Figure 4: Component-Section Lifecycle Condition Curve (Uzarski & Grussing, 2006)

Based on these performance curves, probability distributions for failure can be developed. Figure 5a shows the probability distribution for the time to failure for a hypothetical component-section (Grussing et al., 2006). This curve is derived from the Probability Density Funtion (PDF) of the distribution. Figure 5b relates the probability that the component-section will fail at or before a given year (Grussing et al., 2006). This curve is known as the failure curve and is derived from the Cumulative Density Function (CDF). Since failure is the complement of reliability, taking the inverse of the failure curve will yield the reliability curve, as shown in Figure 5c. Grussing et al. (2006) define reliability as the statistical probability that a component-section will meet or exceed performance standards at a given year in its lifecycle.

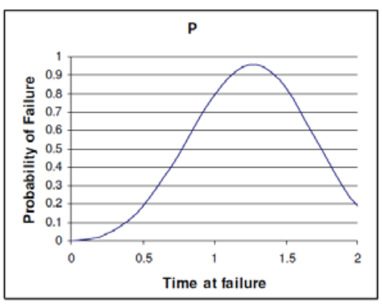


Figure 5a: Failure in year t

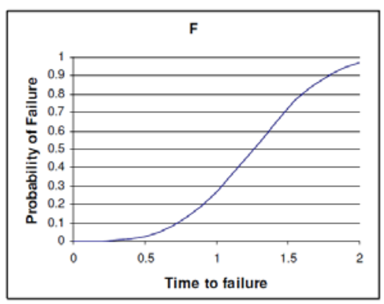


Figure 5b: Failure before year t
(Grussing et al., 2006:3)

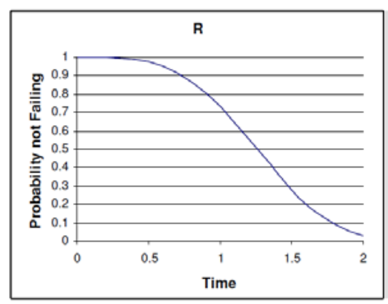


Figure 5c: Performs past past year t

Generally, there are two types of failure rate functions: constant and non-constant. Non-constant failure rate functions are also referred to as time-dependent failure rate functions. Functions of this type take any of several forms, but of these the Weibull model is the most popular because it is a general form with parameters whose specific values influence (1) the final shape of the distribution and (2) the direction of change of the failure rate: increasing, decreasing, or constant (Labi, 2013). These shape and direction changes are accomplished through the use of the shape parameter (α), which influences the final shape of the distribution, and the scale parameter (β), which influences the direction of change of the failure rate.

For use in the BUILDER™ Sustainment Management System, the Weibull probability distribution is used to model the CDF and thus the condition lifecycle curve. According to Grussing et al. (2006:21), "the Weibull statistical distribution represents the probability of time to failure of a component-section in service." This model predicts the CI at a certain point in time, and it assumes that the condition state measured by the CI and the reliability state are proportionally similar (Grussing et al., 2006). The resulting mathematical condition prediction model is provided in Equation 3 (USACE, 2014c):

$$CI = A \times \left(\frac{100}{CI_t} \right)^{-\left(\frac{t}{\beta} \right)^{\alpha}} \tag{3}$$

Where

CI = Predicted Condition

A = Initial Condition CI

CI_t = CI terminal value

t = time, as a percentage of expected service life

β = adjusted service life parameter

α = degradation parameter.

The measurement and prediction of future facility condition trends is essential to a building lifecycle management program (Grussing et al., 2006). However, there are limitations associated with this preditiction method. One limitation is that the Weibull reliability model assumes normal maintenance, but not corrective repairs which may improve condition and/or extend life (Grussing et al., 2014). Therefore, the CI may not be explained by the equation due to a difference in the scale and shape parameters.

Definition of Failure

It is difficult to predict the failure state for a component-section because the true lifespan of a component-section is rarely known (Grussing et al., 2006). The definition of failure is ambiguous and can vary among individuals. As posed by Grussing et al. (2006), does a window component-section fail when the vapor barrier is breached, when it is no longer operable, when a window pane breaks, or by some other criterion? In an attempt to alleviate this vagueness, Grussing et al. (2006) define a quantitative failure state based on an objective Condition Index (CI) metric, which provides a more consistent definition of component failure. The definitions for the CI metric can be found in Table 3.

Table 3: Condition Index Definitions (Grussing & Marrano, 2007)

Condition Index		**Definition**
100-85	Good	Slight serviceability/reliability reduction overall to component.
85-70	Satisfactory	Component serviceability/reliability is degraded but adequate.
70-55	Fair	Component serviceability or reliability is noticeably degraded.
55-40	Poor	Component has significant serviceability or reliability loss.
40-25	Very Poor	Unsatisfactory serviceability or reliability reduction.
25-10	Serious	Extreme serviceability or reliability reduction.
10-0	Failed	Overall degradation is total.

According to Grussing and Liu (2014), failure occurs when the CI falls to approximately 40. At this level, the component-section can no longer serve its intended function sufficiently. To estimate when a component-section will reach this failure level, the lifecycle condition curve is employed. As seen in Figure 6, the example component-section has a service life of 20 years. Therefore the lifecycle curve indicates that the CI will hit the failure level of 40 at the end of its service life (20 years).

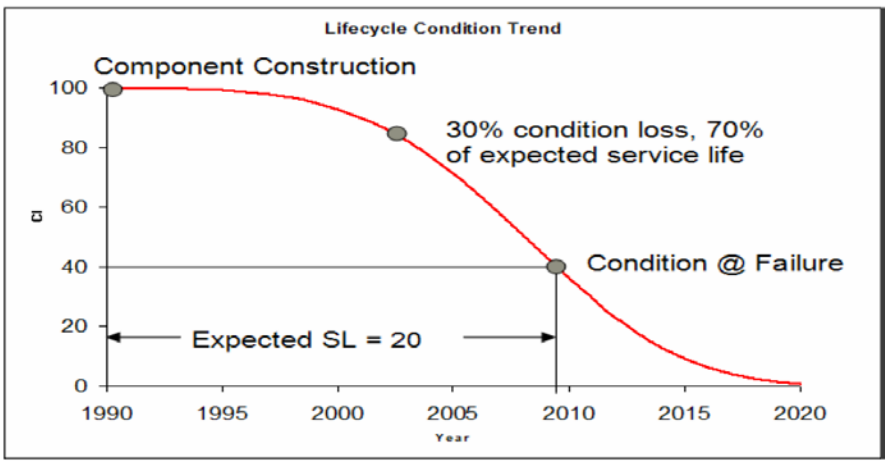


Figure 6: Example Initial Lifecycle Condition Curve (Grussing et al., 2006:4)

Adjusted Lifecycle Condition Trend

The lifecycle condition curve shown in Figure 6 assumes that the expected service life of the component-section equals the initial industry average estimate. Then, as inspections are performed on the component-section, these inspections form the shape of the observed and projected lifecycle curve (Grussing et al., 2006). This is accomplished by adjusting the α and β parameters to fit the lifecycle curve. Figure 7 depicts how collected inspection data are used to readjust the expected service life and lifecycle curve.

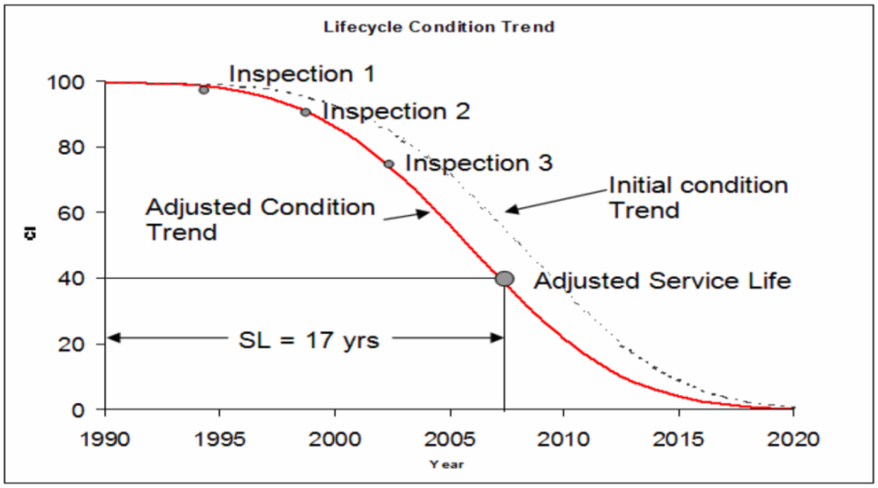


Figure 7: Lifecycle Condition Curve after Inspection (Grussing et al., 2006:6)

Fault Trees

A fault tree is a graphic model of various parallel and sequential combinations of faults that will result in the occurrence of the predefined undesired event (Vesely et al., 1981). In a fault tree, the undesired event is known as the top event. The middle events are known as intermediate events, and the bottom events are known as the basic events. A fault tree thus depicts the logical interrelationships of basic events that lead to the undesired or top event (Vesely et al., 1981).

The logical relationships of the events are shown by logical symbols or gates, as represented in Figure 8. More specifically, these gates show the relationships of events needed for the occurrence of a "higher" event in which the "higher" event is the "output" of the gate and the "lower" events are the "inputs" to the gate (Vesely et al., 1981). There are two basic types of gates in a fault tree: the OR gate and the AND gate. The OR gate is used to show that the output occurs if any of the inputs occur. The AND gate is used to show that the output occurs if all of the inputs occur.

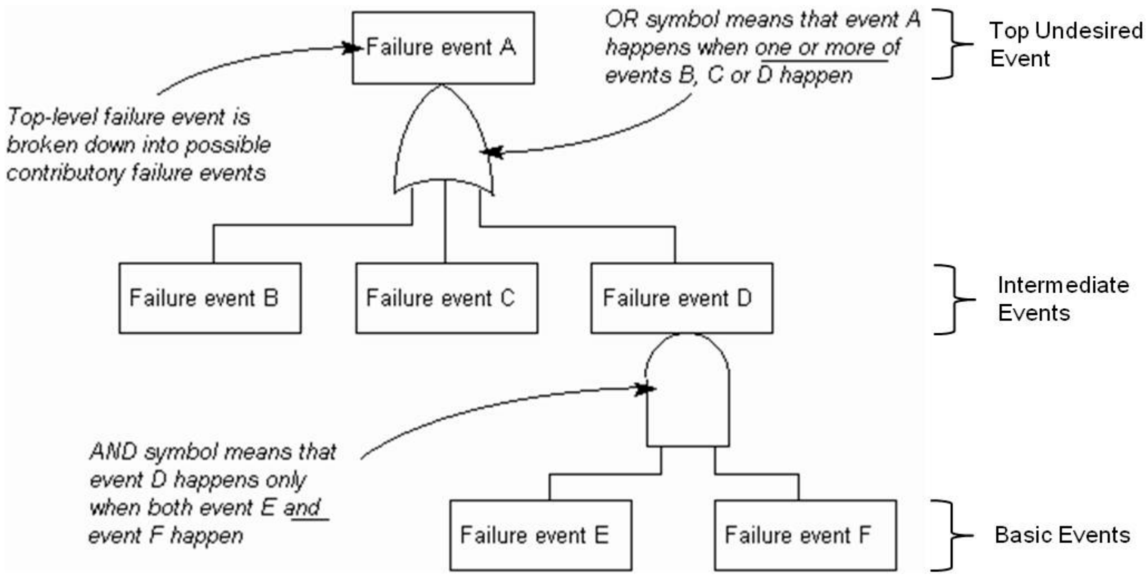


Figure 8: Example Fault Tree Diagram (Straker, 1995)

Fault Tree Analysis

Fault tree analysis is conducted by associating the events in the fault tree with statistical probabilities. The AND logic gate is equivalent to the intersection of the probabilities, and the OR logic gate is equivalent to the union of the probabilities. These probabilities can be found in Equation 4 and Equation 5. Equation 5 assumes that A and B are independent events.

$$P_f(A\ AND\ B) = P_f(A \cap B) = P_f(A) \times P_f(B) \tag{4}$$

$$P_f(A\ OR\ B) = P_f(A \cup B) = P_f(A) + P_f(B) - P_f(A) \times P_f(B) \tag{5}$$

However, if A and B are mutually exclusive events, then $P_f(A \cap B) = 0$ and the probability is found using Equation 6.

$$P_f(A\,OR\,B) = P_f(A \cup B) = P_f(A) + P_f(B) \qquad (6)$$

Another interpretation of these relationships is to recognize that an OR gate indicates the components are functioning in parallel, while an AND gate indicates the components are functioning in series.

Boolean Logic

To paraphrase Fullwood (2000), a fault tree model treats each component or event as either working or not working; hence, the state of the system my be represented by a logical equation composed of the states of the components. This valuable information may also be used to calculate the probability of system failure by replacing each component's Boolean state with the probability for which that component will fail. Simply put, a fault tree can be thought of as a pictorial representation of those Boolean relationships among fault events that cause the top event to occur (Vesely et al., 1981).

However, Ross and Donald (1996) argue that the use of strict probabilistic logic for AND and OR gates is restrictive on the logic of the interaction of events. In many cases, the interrelationship between the basic events, or between vaious branches of the tree, lies somewhere between the extremes of a pure AND and a pure OR gate (Ross & Donald, 1996). To oppose the pure AND and pure OR gates, the concept of fault trees using fuzzy logic is introduced.

Fault Trees with Fuzzy Logic

To paraphrase Ross and Donald (1996), in cases where the fault tree gate is not entirely an AND or an OR gate, certain aggregation operators called Ordered Weighted Averaging (OWA) can prove extremely powerful. OWA operators allow the modeler of a fault tree to adjust the degree of the OR'ing or AND'ing in the tree network (Yager, 1988). When utilizing the OWA operators, classical AND and OR gates are special cases.

Ross and Donald (1996) present the following methodology for analyzing fault trees with fuzzy logic. The OWA operator is comprised of two vectors multiplied together: *W*, a weighting vector, shown in Equation 7:

$$W = \begin{bmatrix} W_1 & W_2 & W_n \end{bmatrix} \tag{7}$$

and *B*, a vector of the basic probabilities of a fault tree that is ordered to express the elements of a gate, shown in Equation 8:

$$B = \begin{bmatrix} b_1 \\ b_2 \\ b_n \end{bmatrix} \tag{8}$$

These vectors are then multiplied to yield a scalar result that is called an ORAND operator. This ORAND operator is very flexible, in that logics between the extremes of a pure AND or OR gate can be modeled.

The ORAND operator, F, is defined as $F(A_1, A_2, \ldots, A_n)$, where A_i is the i^{th} basic event probability. For example, if we have $n = 4$ and the A_i probabilities are ordered from highest to lowest we get:

$$F(A_1, A_2, A_3, A_4) = WB = W_1 b_1 + W_2 b_2 + W_3 b_3 + W_4 b_4 \tag{9}$$

where b_i is the ith largest element in the collection $A_1, A_2, \ldots, A_n$.

Normalization is preserved with $\sum W_i = 1$. Furthermore, the measures of ANDness and ORness in the value F can be determined using the following relationships:

$$ORness(W) = \sum_{j=1}^{n} \frac{(n-j)}{(n-1)} W_j \tag{10}$$

$$ANDness(W) = 1 - ORness(W) \tag{11}$$

Moreover, a measure of dispersion can also be developed which gives a metric of the distance from the pure AND or OR gates. The dispersion is a minimum for an AND or OR gate and a maximum when A_i = 1/n for all i.

$$dispersion(W) = -\sum_{j=1}^{n} W_j \ln W_j \tag{12}$$

An example of the application of fuzzy logic to fault trees is given in Chapter III.

Summary

This literature review provided an overview of the existing literature on the key topics to this research effort. The topics described in this chapter included a background on the BUILDER™ system and an explanation of the Condition Index metric, a discussion of facility performance prediction through the use of service life, and a consistent definition of failure by using the Weibull probability distribution. It closed with a discussion of fault trees and the use of fault trees with fuzzy logic. The following chapter presents the use of the Weibull probability distribution and fault trees with fuzzy logic to define failure within the BUILDER™ system.

III. Methodology

Chapter Overview

This chapter provides the methodology used in the research effort. The first step in calculating the probability of failure is identifying which probability functions are appropriate. Next, the probabilities found from the probability functions are "rolled-up" to higher infrastructure levels by using logic trees, probability theory, and fuzzy logic. The probabilities found from this method will be further analyzed in Chapter IV.

Probability Functions

The condition prediction model assumes that the condition state measured by the Condition Index (CI) and the reliability state are proportionally similar (Grussing et al., 2006). The main difference between the CI curve and the reliability curve is the CI curve is based on a scale from 0 to 100 and the reliability curve is based on a scale from 0.0 to 1.0. This is because the reliability curve is based on the cumulative distribution function which has the following properties (Labi, 2013): $R(t) \geq 0$, $R(\infty) = 0$, and $R(0) = 1$.

Labi (2013) explains that due to the fact that reliability is a likelihood or a probability, failure is regarded as a random event. Reliability may be defined generally as the ability of a system (or component thereof) to perform its required functions or to achieve its established performance objectives under a given set of conditions at a given point in time (Labi, 2013). As previously mentioned, failure is the mathematical complement of reliability. Because of this relationship, the probability that a system will fail (that is, not perform satisfactorily in terms of the given performance criterion over a given time period t) can be expressed as (Labi, 2013):

$$F(t) = 1 - R(t) = 1 - P(T \geq t) = P(T < t) \tag{13}$$

Where

T = the time taken for the system to "fail".

These cumulative density function relationships can be seen in Figure 9.

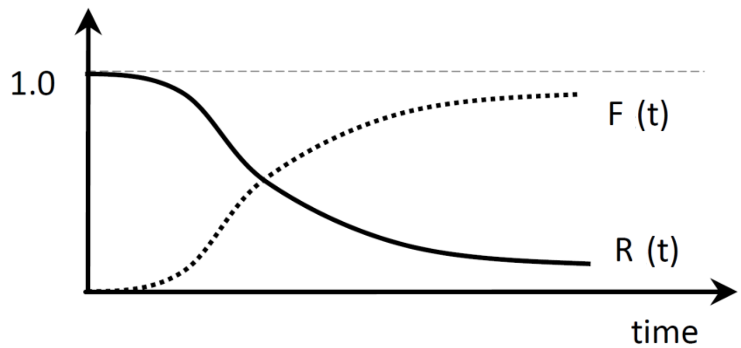


Figure 9: Time Trend of the Probability of System Failure and Reliability (Labi, 2013)

The equation used in this research to calculate the reliability uses the Weibull cumulative probability distribution function. This specific equation is repeated and provided in Equation 14 (adapted from Grussing et al., 2014):

$$R(t) = A \times \left(\frac{1}{CI_t} \right)^{-\left(\frac{t}{\beta}\right)^{\alpha}} \tag{14}$$

Where

R(t) = reliability

A = initial reliability

CI_t = Condition Index at failure

t = normalized age as a percentage of design service life

β = service life adjustment (scale) parameter

α = reliability degradation (shape) parameter.

Taking the inverse of the reliability equation produces the equation for the probability of failure found in Equation 15.

$$F(T \le t) = 1 - \left[A \times \left(\frac{1}{CI_t} \right)^{-\left(\frac{t}{\beta}\right)^{\alpha}} \right] \tag{15}$$

Where

$F(T \le t)$ = failure

A = initial reliability

CI_t = Condition Index at failure

t = normalized age as a percentage of design service life

β = service life adjustment (scale) parameter

α = reliability degradation (shape) parameter.

Probability Roll-Up

Since the design service life is known for each of the component-sections, the probability of failure can initially only be calculated at the component-section level. Just as the CI is “rolled up” to be calculated at the component, system, and ultimately building level, this research does the same with the probability of failure. Unlike CI, however, replacement cost throughout the system is ignored and a different method of relating components to each other is implemented. The first piece of information needed for the “roll-up” of probabilities of failure to occur are the relationships between the component-sections and components, and the components and the systems of these components. Developing these relationships is done through fault trees with fuzzy logic.

Fault Trees with Fuzzy Logic

As discussed in Chapter II, the methodology for analyzing fault trees with fuzzy logic is attributed to Ross and Donald (1996). To elaborate on their ideas, the authors present the following example of a simple fault tree modeled using the Ordered Weighted Averaging (OWA) operators. As shown in Figure 10, there are four basic events which comprise a general ORAND gate. The probabilities of failure of each of the basic events A1, A2, A3, and A4 are 0.6, 0.85, 0.3, and 0.5, respectively.

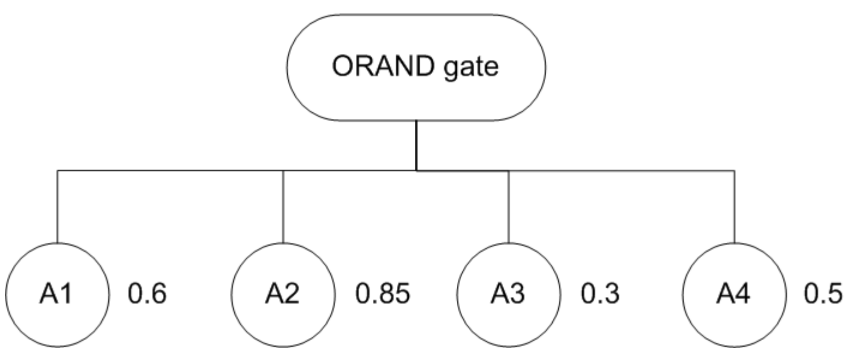


Figure 10: Example Fault Tree with Fuzzy Logic (Adapted from Ross & Donald, 1996)

In a probabilistic analysis, a pure AND gate (assuming the basic events are independent) is equivalent to the intersection of the probabilities of the basic events. As discussed in Chapter II and shown in Equation 2, the intersection is represented by the simple product of the four failure probabilities, by which Equation 16 yields a value of 0.0765.

$$\begin{aligned} P(A \cap B \cap C \cap D) &= P(A) \times P(B) \times P(C) \times P(D) \\ &= 0.6 \times 0.85 \times 0.3 \times 0.5 = 0.0765 \end{aligned} \tag{16}$$

The pure OR gate is equivalent to the union of the probabilities which is determined through the sums and products of various combinations of the four basic event probabilities displayed in Equation 17 and simplified in Equation 18. The value of the pure OR is calculated to be 0.979.

$$\begin{aligned} P(A \cup B \cup C \cup D) = {} & P(A) + P(B) + P(C) + P(D) - P(A \cap B) - P(A \cap C) \\ & - P(A \cap D) - P(B \cap C) - P(B \cap D) - P(C \cap D) \\ & + P(A \cap B \cap C) + P(A \cap B \cap D) + P(A \cap C \cap D) \\ & + P(B \cap C \cap D) - P(A \cap B \cap C \cap D) \end{aligned} \tag{17}$$

$$\begin{aligned} P(A \cup B \cup C \cup D) = {} & P(A) + P(B) + P(C) + P(D) - P(A)P(B) - P(A)P(C) - \\ & P(A)P(D) - P(B)P(C) - P(B)P(D) - P(C)P(D) + \\ & P(A)P(B)P(C) + P(A)P(B)P(D) + P(A)P(C)P(D) + \\ & P(B)P(C)P(D) - P(A)P(B)P(C)P(D) \\ = {} & 0.6 + 0.85 + 0.3 + 0.5 - 0.51 - 0.18 - 0.3 - 0.255 - 0.425 - \\ & 0.15 + 0.153 + 0.255 + 0.09 + 0.1275 - 0.0765 = 0.979 \end{aligned} \tag{18}$$

The pure AND gate reflects the fact that, as more numbers are multiplied by one another, the result approaches a very small number in relation to the values of any of the basic events. Conversely, the OR gate represents that as more numbers are added to one another, the result approaches a very large number in relation to the values of any of the basic events. These principles are validated by the pure AND gate value of 0.0765 being strictly less than or equal to the minimum basic event of 0.3, and the pure OR gate value of 0.979 being strictly greater than or equal to the maximum basic event of 0.85.

As previously established, the pure AND and pure OR situations of the OWA operators represent the extremes of the probabilistic analysis. The use of pure AND and pure OR gates leaves no margin for error, especially if one or more of the gates happens to be assumed as the opposite of what it truly is. The OWA operators produce an aggregation type operator that always lies between the AND and the OR aggregation, and so OWA operators can be thought of as a kind of ORAND operator (Yager, 1988:186).

As detailed in Chapter II, the OWA operator is comprised of two vectors multiplied together: W, a weighting vector, and B, a vector of the basic probabilities of a fault tree that is ordered to express the elements of a gate. In the OWA method, each weight, W_i, is associated with a particular ordered position rather than a particular element (Yager, 1988:185). It will be shown later that the OR gate is associated with the largest probability in vector B, and the AND gate is associated with the smallest probability in vector B.

Figure 10 depicted the four basic events with each event's corresponding probability. These events make up the probabilities vector, B, in which the probabilities are ordered from largest to smallest:

$$B = \begin{bmatrix} 0.85 \\ 0.6 \\ 0.5 \\ 0.3 \end{bmatrix} \tag{19}$$

Then, for this example, the OWA method uses the following weighting vector, *W*, while keeping in mind that the weights should add up to a value of 1.0:

$$W = \begin{bmatrix} 0.2 & 0.3 & 0.1 & 0.4 \end{bmatrix} \tag{20}$$

These vectors are then multiplied to yield a scalar result that is called an ORAND operator, *F*:

$$\begin{aligned} F = WB &= \begin{bmatrix} 0.2 & 0.3 & 0.1 & 0.4 \end{bmatrix} \begin{bmatrix} 0.85 \\ 0.6 \\ 0.5 \\ 0.3 \end{bmatrix} \\ &= (0.2 \times 0.85) + (0.3 \times 0.6) + (0.1 \times 0.5) + (0.4 \times 0.3) = 0.52 \end{aligned} \tag{21}$$

Ross and Donald (1996) describe that this particular ORAND gate is combining 20% of a pure OR gate (which supports the maximal basic event of 0.85), 40% of a pure AND gate (which supports the minimal basic event of 0.30), and a combined total of 40% (30% and 10%) influence from the intermediate valued basic events (i.e., those with probabilities of 0.6 and 0.5).

Probabilities Vector (B)

The method for calculating the probability of failure was previously presented in Equation 15. For this research, $F(T \leq t)$ is the dependent variable of probability of failure which will always possess a value between 0.00 and 1.00 since it represents a quantitave probability. The initial reliability, A, held a value of 1.00 for the purposes of this research. This is because a newly installed component-section will always have an initial reliability of 100% (1.00) at time $t = 0$. The Condition Index at failure, CI_t, holds a value of 0.37 in this research. This may seem contradictory compared to the definition of failure given in Chapter II as a Condition Index value of 40. The new value of 37 is based on how the CI scale is defined. Based on the definitions found in Table 3, failure occurs when the CI falls to approximately 40. However, Table 4 displays an alternative CI scale with corresponding definitions. In this table, failure corresponds to a CI of 37 and below where the component-section is barely able to perform or the overall degradation is total.

Table 4: Alternative Condition Index Definitions (Adapted from USACE, 2014a)

CI		**Definition**
100	G+	Entire component-section or sample free of observable defects.
99-93	G	No component-section or sample serviceability or reliability reduction.
92-86	G-	Slight or no serviceability or reliability reduction overall to component-section.
85-75	A+	Component-section serviceability or reliability is degraded but adequate.
74-65	A	Component-section serviceability or reliability is definitely impaired.
64-56	A-	Component-section has significant serviceability or reliability loss.
55-37	R+	Significant serviceability or reliability reduction in component-section.
36-11	R	Severe serviceability or reliability reduction, such that it is barely able to perform.
10-0	R-	Overall degradation is total.

The fourth variable in Equation 15 is time, t, which is the component-section's normalized age as a percentage of its design service life. This value can range from 0.00 if the component-section is brand new, to an infinite value that is dependent on the year the component-section was installed. The last two variables are the beta, β, and alpha, α, parameters, respectively. As discussed in Chapter II, the β is the scale parameter or, in this research, the service life adjustment parameter. This paramter influences the direction of change of the failure rate: increasing, decreasing, or constant (Labi, 2013:16-17). The shape parameter, α, in this research is the reliability degradation parameter. This parameter influences the final shape of the distribution (Labi, 2013:16-17).

In this research, β is assumed to be a value of 1.00 because the service life adjustment factor scales the Weibull curve in or out; so when β is 1.00, there is no scaling and the adjusted service life equals the expected service life (Grussing, 2014a). The alpha parameter, α, is based on an assumption of condition loss over time, and initially for all component-sections a "70-30" curve is assumed which means that over the first 70% of the component-section's life, there is a 30% drop in Condition Index (Grussing, 2014a). With this assumption, the alpha parameter is calculated to equal 2.64.

The results from probability of failure calculations are presented in tables such as Table 5. In this example, the probabilities of failure are calculated for each of the component-sections found in the D2010 Plumbing Fixtures component. This component, among others, make up the D20 Plumbing system. As provided in Table 5, the D2010 Plumbing Fixtures component is made up of eight component-sections, each with its own design life. This example then assumes that each of the component-sections were installed 10 years ago. These values are then substituted into Equation 15 which yields each of the component-section's respective probability of failure.

Table 5: Obtaining Component-Section Failure Probabilities

Component	Component-Section	Design Life	Time, t	F(T≤t)
D2010 Plumbing Fixtures	D201001 Waterclosets	25	10	0.085
D2010 Plumbing Fixtures	D201002 Urinals	25	10	0.085
D2010 Plumbing Fixtures	D201003 Lavatories	25	10	0.085
D2010 Plumbing Fixtures	D201004 Sinks	25	10	0.085
D2010 Plumbing Fixtures	D201005 Showers/Tubs	25	10	0.085
D2010 Plumbing Fixtures	D201006 Drinking Fountains & Coolers	10	10	0.630
D2010 Plumbing Fixtures	D201007 Bidets	25	10	0.085
D2010 Plumbing Fixtures	D201090 Other Plumbing Fixtures	15	10	0.289

Weighting Vector (W)

According to Yager (1988), there are at least two ways that can be used to obtain the W_i values. The first approach is to use some kind of learning mechanism with sample data, arguments, and associated aggregated values and try to fit the weights to this collection of sample data. This process might involve the use of some kind of regression model (Yager, 1988). Yager also describes a second approach of giving some semantics or meaning to the W_i values. Based upon these semantics, a risk analyst can have a decision-maker directly provide the values for the W_i values.

In this research, the second approach Yager proposed was used. The W_i values became the consequence of failure factor in the risk equation described in Equation 2. Additionally in this research, the consequence was represented by importance values. To represent the importance of the component-sections, subcomponent weight factors were used. As discussed previously in Chapter I, subcomponent weight factors indicate the relative importance of each subcomponent in terms of the cost to replace and the importance or criticality to the overall component (USACE, 2014a). Subcomponent weight factors range from values of 0.01 to 1.00.

Table 6: Obtaining Component-Section Weight Factor

Component	**Component-Section**	**Subcomponent**	**Subcomponent Weight Factor**
D2010 Plumbing Fixtures	D201001 Waterclosets	Flush Valve Assembly	0.730
D2010 Plumbing Fixtures	D201001 Waterclosets	Piping/Fittings	1.000
D2010 Plumbing Fixtures	D201001 Waterclosets	Seat/Cover	0.120
D2010 Plumbing Fixtures	D201001 Waterclosets	Unit	0.700
		AVERAGE	0.638

The subcomponent weight factors for the D201001 Waterclosets component-section are used as an example in Table 6. This component-section is made up of four subcomponents, with the respective subcomponent weight factors ranging from 0.120 to 1.000. To find the weight factor for the component-section, the subcomponent weight factors are averaged. In this case, the weight factor for the component-section D201001 Waterclosets becomes 0.638.

In keeping with the methodology for analyzing fault trees using fuzzy logic, the weights in the weighting vector must sum to a value of 1.00. This can be accomplished by standardizing each of the component-section weights. An example of this weight factor standardization is displayed in Table 7. To achieve standardization, each of the component-section weight factors derived from averaging the subcomponent weight factors was summed. Then each of the average component-section weight factors was divided by the sum in order to produce the standardized component-section weight factor.

Table 7: Component-Section Weight Factor Standardization

Component	**Component-Section**	**Average Weights**	**Weights Standardized**
D2010 Plumbing Fixtures	D201001 Waterclosets	0.638	0.111
D2010 Plumbing Fixtures	D201002 Urinals	0.407	0.071
D2010 Plumbing Fixtures	D201003 Lavatories	0.650	0.114
D2010 Plumbing Fixtures	D201004 Sinks	0.538	0.094
D2010 Plumbing Fixtures	D201005 Showers/Tubs	1.000	0.175
D2010 Plumbing Fixtures	D201006 Drinking Fountains & Cooers	1.000	0.175
D2010 Plumbing Fixtures	D201007 Bidets	0.493	0.086
D2010 Plumbing Fixtures	D201090 Other Plumbing Fixtures	1.000	0.175
	SUM	5.725	1.000

After finding the weight factors for each of the component-sections, the next step was to find the weights for each of the components comprising the system. To measure the importance of the components, the Component Importance Index (CII) values was used. The CII is a measure that conveys the relative importance of a building component by gauging the interruptability and impact of a component failure on such aspects as mission, life safety, quality of life, and secondary effects on other components (Grussing, 2014a).

However, there are two limitations associated with these CII values. First, the CII values were based on preliminary surveys of perceived component importance, but with a small number of respondents as a wide range of variability of responses in some cases (Grussing, 2014a). Second, the component type is not in the UNIFORMAT II naming convention as shown in the original CII values listed in Appendix B. Therefore, these components had to be classified into UNIFORMAT II components. The UNIFORMAT II coded CII Values can be found in Appendix D.

As with the component-section weight factors, the CII values are also an average of the original component CII values that make up that UNIFORMAT II component, as the UNIFORMAT II component may be made up of more than one of the original components. This principle can be seen in Appendix C. For example, the UNIFORMAT II component D2010 Plumbing Fixtures is made up of two original components: Plumbing Fixtures and Sump. Therefore, the CII value for D2010 Plumbing Fixtures would be an average of the Plumbing Fixtures and Sump CII values. Additionally, as with the component-section weight factors, the CII values must sum to a value of 1.00 and therefore need to be standardized. This standardization is displayed in Table 8.

Table 8: Component Importance Index Values Standardization

System	Component	CII Values Averaged	CII Values Standardized
D20 Plumbing	D2010 Plumbing Fixtures	0.447	0.183
D20 Plumbing	D2020 Domestic Water Distribution	0.542	0.222
D20 Plumbing	D2030 Sanitary Waste	0.628	0.257
D20 Plumbing	D2040 Rain Water Drainage	0.522	0.214
D20 Plumbing	D2090 Other Plumbing Systems	0.303	0.124
	SUM	2.441	1.000

System Probability of Failure

Just as the CI is “rolled up” from the component-section level to the component level and then system level in the SCI model, the same is done for the probability of failure. This “roll up” is accomplished through using fault trees with fuzzy logic. By weighting each of the component-section’s probability of failure by its consequence of failure, this results in the probability of failure for the respective component. Then, the system probability of failure is found by weighting each of the respective component's probability of failure by its consequence of failure.

The reason why the probability of failure is only "rolled-up" to the system level is because building failure does not occur at the facility level. That is, entire facilities do not fail all at once, except in the case of structural failure. Instead, failure occurs at the system level. Additionally, this is the level targeted by civil engineering work orders.

Model Validation

One important step in model creation is the validation and verification of a model. The probabilistic failure model is validated using real-world failure data. These data are obtained from previous Civil Engineering Work Orders (WOs) stored in the Interim Work Information Management System (IWIMS). The work orders are from a period of one fiscal year, and are filtered down to only emergency and urgent work orders. The reason only emergency and urgent WOs are analyzed is because these WOs are the most related to system failure. This research assumes that an emergency or urgent WO to "Fix HVAC System" means the HVAC system has failed, while a scheduled sustainment WO to "Fix HVAC System" means the system has degraded but has not failed.

The WOs are descriptive enough to document that a system in a certain facility has failed. Once the facility number is obtained, the system in that facility is found in BUILDER™. Then the system is broken down to the component, then component-section level, and the service lives of each of the component-sections is input into the model to compute the probability of failure for the system. Lastly, the probability of failure based on the service lives of the component-sections is compared to the System Condition Index (SCI) produced by BUILDER^{TM}.

In addition to assessing systems that have failed, a random sample of systems that have not failed is also assessed. This process is the same as for the failed systems and the service lives of each of the component-sections are found in BUILDER^{TM} then input into the model to compute the probability of failure. For these non-failed systems, their probabilities of failure should be lower than failed systems. For completeness, the non-failed systems are compared to the SCI found in BUILDER^{TM}.

Summary

This chapter provided the steps to construct a probabilistic risk assessment model. First, the probabilities of failure at the component-section level were found using the Weibull probability distribution. Next, the probabilities found at the component-section level were weighted by the consequence of failure values in order to be "rolled-up" to the component and system levels according to the methodology of fault trees with fuzzy logic. Finally, a model validation and verification step using real-world WOs was described. Analysis and results to this methodology are discussed in the following chapter.

IV. Analysis and Results

Chapter Overview

This chapter provides the analysis and results from this research effort. First, the resulting probabilistic models are presented for the plumbing, HVAC, fire protection, and electrical systems. Next, efforts to validate these models are made by using real-world Work Order (WO) data. These WO data are input into the probabilistic models and then a contingency analysis is conducted to determine the models' predictive ability.

Resulting Probabilistic Models

The main focus of this research is to create models to predict the probability of failure at the component-section, component, and system levels. Using the methodology described in Chapter III, probabilistic models have been developed for the following building systems: plumbing, HVAC, fire protection, and electrical. There are a total of 17 building systems designated by UNIFORMAT II classification (Charette & Marshall, 1999). These four systems comprise the greater part of the services major group; however, the fifth system in the services major group, conveying, was not addressed in this research.

The four building systems that are investigated (plumbing, HVAC, fire protection, and electrical) were chosen because their failures are visible to the users. For example, it is easy to notice when an electrical system has failed because it is indicated by a loss of power. Conversely, it is much harder to notice when the superstructure system, better known as the structural frame, has failed. The ability for these failures to be noticed is crucial during the validation of the probabilistic model.

The following four tables display the probabilistic models for each of the four systems under investigation. The model for the plumbing system is presented in Table 9, the HVAC system model in Table 10, the fire protection system model in Table 11, and the electrical system model in Table 12. These models contain all of the component-sections and components comprising each of the systems. These models also display the probabilities of failure at the ages of 10, 20, 30, 40, and 50 years.

Each of these models can be interpreted by using the example fault tree with fuzzy logic given in Figure 11. This example analyzes the D20 Plumbing System at a time of 20 years. This figure is reminiscent of the example fault tree with fuzzy logic presented in Figure 10. The probabilities of failure for each of the five components and for the overall system are represented by the ORAND operator, *F(T ≤ 20)*.

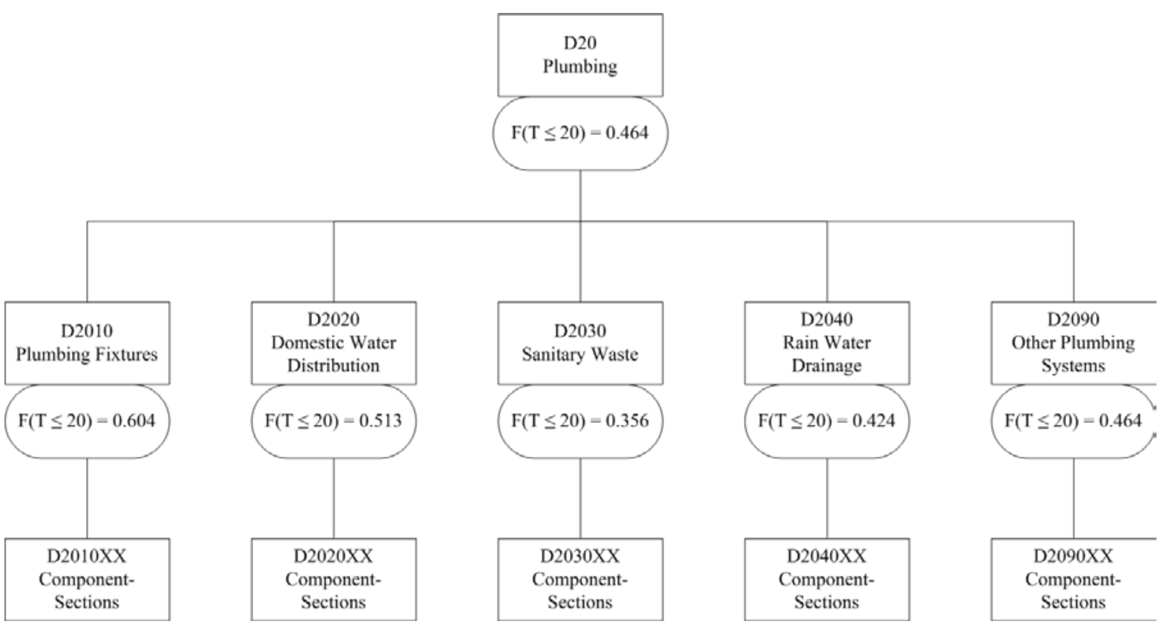


Figure 11: Example Fault Tree with Fuzzy Logic for D20 Plumbing System

Table 9: D20 Plumbing System Probabilistic Model

	Component-Section (C-S)	C-S Wts	Standardized	C-S F(T≤10)	Comp F(T≤10)	C-S F(T≤20)	Comp F(T≤20)	C-S F(T≤30)	Comp F(T≤30)	C-S F(T≤40)	Comp F(T≤40)	C-S F(T≤50)	Comp F(T≤50)
D2010	D201006 Drinking Fountains & Coolers	1.000	0.175	0.630	0.216	0.998	0.604	1.000	0.869	1.000	0.979	1.000	0.999
	D201090 Other Plumbing Fixtures	1.000	0.175	0.289		0.881		0.998		1.000		1.000	
	D201001 Waterclosets	0.638	0.111	0.085		0.424		0.800		0.968		0.998	
	D201002 Urinals	0.407	0.071	0.085		0.424		0.800		0.968		0.998	
	D201003 Lavatories	0.650	0.114	0.085		0.424		0.800		0.968		0.998	
	D201004 Sinks	0.538	0.094	0.085		0.424		0.800		0.968		0.998	
	D201005 Showers/Tubs	1.000	0.175	0.085		0.424		0.800		0.968		0.998	
	D201007 Bidets	0.493	0.086	0.085		0.424		0.800		0.968		0.998	
		5.725											
D2020	D202090 Other Domestic Water Supply	1.000	0.189	0.833	0.222	1.000	0.513	1.000	0.805	1.000	0.943	1.000	0.977
	D202002 Valves & Hydrants	1.000	0.189	0.085		0.424		0.800		0.968		0.998	
	D202003 Domestic Water Equipment	1.000	0.189	0.085		0.424		0.800		0.968		0.998	
	D202004 Insulation & Identification	1.000	0.189	0.085		0.424		0.800		0.968		0.998	
	D202005 Specialties	1.000	0.189	0.085		0.424		0.800		0.968		0.998	
	D202001 Pipes & Fittings	0.303	0.057	0.014		0.085		0.227		0.424		0.630	
		5.303											
D2030	D203002 Vent Pipe & Fittings	1.000	0.205	0.085	0.071	0.424	0.356	0.800	0.678	0.968	0.836	0.998	0.884
	D203003 Floor Drains	1.000	0.205	0.085		0.424		0.800		0.968		0.998	
	D203004 Sanitary & Vent Equipment	1.000	0.205	0.085		0.424		0.800		0.968		0.998	
	D203005 Insulation & Identification	1.000	0.205	0.085		0.424		0.800		0.968		0.998	
	D203001 Waste Pipe & Fittings	0.411	0.084	0.014		0.085		0.227		0.424		0.630	
	D203090 Other Sanitary Waste	0.475	0.097	0.002		0.014		0.041		0.085		0.147	
		4.886											
D2040	D204001 Pipe & Fittings	1.000	0.225	0.085	0.085	0.424	0.424	0.800	0.800	0.968	0.968	0.998	0.998
	D204002 Roof Drains	0.548	0.123	0.085		0.424		0.800		0.968		0.998	
	D204003 Rainwater Drainage Equipment	0.901	0.203	0.085		0.424		0.800		0.968		0.998	
	D204004 Insulation & Identification	1.000	0.225	0.085		0.424		0.800		0.968		0.998	
	D204090 Other Rain Water Drainage System	1.000	0.225	0.085		0.424		0.800		0.968		0.998	
		4.449											
D2090	D209001 Special Piping Systems	0.436	0.088	0.289	0.103	0.881	0.464	0.998	0.817	1.000	0.971	1.000	0.998
	D209002 Acid Waste Systems	1.000	0.202	0.085		0.424		0.800		0.968		0.998	
	D209003 Interceptors	1.000	0.202	0.085		0.424		0.800		0.968		0.998	
	D209004 Pool Piping & Equipment	1.000	0.202	0.085		0.424		0.800		0.968		0.998	
	D209005 Compressed Air System	1.000	0.202	0.085		0.424		0.800		0.968		0.998	
	D209090 Other Special Plumbing Systems	0.508	0.103	0.085		0.424		0.800		0.968		0.998	
		4.944											

	Component (Comp)	Comp Wts	Standardized	Comp F(T≤10)	System F(T≤10)	Comp F(T≤20)	System F(T≤20)	Comp F(T≤30)	System F(T≤30)	Comp F(T≤40)	System F(T≤40)	Comp F(T≤50)	System F(T≤50)
D20	D2010 Plumbing Fixtures	0.447	0.183	0.216		0.604		0.869		0.979		0.999	
	D2020 Domestic Water Distribution	0.542	0.222	0.222		0.513		0.805		0.943		0.977	
	D2090 Other Plumbing Systems	0.303	0.124	0.103	0.138	0.464	0.464	0.817	0.785	0.971	0.931	0.998	0.964
	D2040 Rain Water Drainage	0.522	0.214	0.085		0.424		0.800		0.968		0.998	
	D2030 Sanitary Waste	0.628	0.257	0.071		0.356		0.678		0.836		0.884	
		2.441											

Table 10: D30 HVAC System Probabilistic Model

	Component-Section (C-S)	C-S Avg	Standardized	C-S F(T≤10)	Comp F(T≤10)	C-S F(T≤20)	Comp F(T≤20)	C-S F(T≤30)	Comp F(T≤30)	C-S F(T≤40)	Comp F(T≤40)	C-S F(T≤50)	Comp F(T≤50)
D3010	D301001 Oil Supply System	1.000	0.139	0.147	0.126	0.630	0.557	0.945	0.884	0.998	0.973	1.000	0.989
	D301003 Steam Supply System	1.000	0.139	0.147		0.630		0.945		0.998		1.000	
	D301004 Hot Water Supply System	1.000	0.139	0.147		0.630		0.945		0.998		1.000	
	D301006 Wind Energy Supply System	1.000	0.139	0.147		0.630		0.945		0.998		1.000	
	D301007 Coal Supply System	1.000	0.139	0.147		0.630		0.945		0.998		1.000	
	D301005 Solar Energy Systems	1.000	0.139	0.085		0.424		0.800		0.968		0.998	
	D301090 Other Energy System	1.000	0.139	0.085		0.424		0.800		0.968		0.998	
	D301002 Gas Supply System	0.204	0.028	0.014		0.085		0.227		0.424		0.630	
		7.204											
D3020	D302002 Furnaces	0.526	0.114	0.289	0.117	0.881	0.491	0.998	0.801	1.000	0.944	1.000	0.990
	D302004 Auxiliary Equipment	0.648	0.141	0.147		0.630		0.945		0.998		1.000	
	D302005 Equipment Thermal Insulation	1.000	0.217	0.147		0.630		0.945		0.998		1.000	
	D302003 Fuel-Fired Unit Heaters	0.425	0.092	0.085		0.424		0.800		0.968		0.998	
	D302001 Boilers	1.000	0.217	0.053		0.289		0.630		0.881		0.978	
	D302090 Other Heat Generating Systems	1.000	0.217	0.053		0.289		0.630		0.881		0.978	
		4.599											
D3030	D303090 Other Cooling Generating Systems	0.090	0.043	0.289	0.154	0.881	0.641	0.998	0.947	1.000	0.998	1.000	1.000
	D303001 Chilled Water Systems	1.000	0.478	0.147		0.630		0.945		0.998		1.000	
	D303002 Direct Expansion Systems	1.000	0.478	0.147		0.630		0.945		0.998		1.000	
		2.090											
D3040	D304007 Exhaust Systems	1.000	0.163	0.630	0.236	0.998	0.684	1.000	0.920	1.000	0.983	1.000	0.997
	D304008 Air Handling Units	1.000	0.163	0.289		0.881		0.998		1.000		1.000	
	D304001 Air Distribution, Heating & Cooling	0.310	0.050	0.147		0.630		0.945		0.998		1.000	
	D304003 Hot Water Distribution Systems	1.000	0.163	0.147		0.630		0.945		0.998		1.000	
	D304004 Change Over Distribution Systems	1.000	0.163	0.147		0.630		0.945		0.998		1.000	
	D304006 Chilled Water Distribution Systems	1.000	0.163	0.147		0.630		0.945		0.998		1.000	
	D304002 Steam Distribution Systems	0.436	0.071	0.053		0.289		0.630		0.881		0.978	
	D304005 Glycol Distribution Systems	0.219	0.036	0.053		0.289		0.630		0.881		0.978	
	D304090 Other Distribution Systems	0.178	0.029	0.053		0.289		0.630		0.881		0.978	
		6.142											
D3050	D305003 Fan Coil Units	1.000	0.208	0.289	0.152	0.881	0.597	0.998	0.892	1.000	0.982	1.000	0.998
	D305001 Unit Ventilators	1.000	0.208	0.147		0.630		0.945		0.998		1.000	
	D305006 Package Units	1.000	0.208	0.147		0.630		0.945		0.998		1.000	
	D305002 Unit Heaters	1.000	0.208	0.085		0.424		0.800		0.968		0.998	
	D305005 Electric Heating	0.273	0.057	0.085		0.424		0.800		0.968		0.998	
	D305090 Other Terminal & Package Units	0.272	0.057	0.085		0.424		0.800		0.968		0.998	
	D305004 Fin Tube Radiation	0.264	0.055	0.053		0.289		0.630		0.881		0.978	
		4.808											

	Component-Section (C-S)	C-S Avg	Standardized	C-S F(T≤10)	Comp F(T≤10)	C-S F(T≤20)	Comp F(T≤20)	C-S F(T≤30)	Comp F(T≤30)	C-S F(T≤40)	Comp F(T≤40)	C-S F(T≤50)	Comp F(T≤50)
D3060	D306002 Electronic Controls	0.565	0.124	0.630	0.299	0.998	0.711	1.000	0.932	1.000	0.992	1.000	1.000
	D306003 Pneumatic Controls	0.565	0.124	0.630		0.998		1.000		1.000		1.000	
	D306090 Other Controls Instrumentation	0.433	0.095	0.630		0.998		1.000		1.000		1.000	
	D306001 HVAC Controls	1.000	0.219	0.147		0.630		0.945		0.998		1.000	
	D306005 Gas Purging Systems	1.000	0.219	0.147		0.630		0.945		0.998		1.000	
	D306004 Instrument Air Compressors	1.000	0.219	0.085		0.424		0.800		0.968		0.998	
		4.563											
D3070	D307001 Water Side Testing & Balancing	1.000	0.250	0.147	0.147	0.630	0.630	0.945	0.945	0.998	0.998	1.000	1.000
	D307002 Air Side Testing & Balancing	1.000	0.250	0.147		0.630		0.945		0.998		1.000	
	D307003 HVAC Commissioning	1.000	0.250	0.147		0.630		0.945		0.998		1.000	
	D307090 Other Systems Testing & Balancing	1.000	0.250	0.147		0.630		0.945		0.998		1.000	
		4.000											
D3090	D309090 Other Special Mechanical Systems	0.234	0.105	0.630	0.198	0.998	0.669	1.000	0.951	1.000	0.998	1.000	1.000
	D309001 General Construction Items	1.000	0.448	0.147		0.630		0.945		0.998		1.000	
	D309002 Refrigeration Systems	1.000	0.448	0.147		0.630		0.945		0.998		1.000	
		2.234											

	Component (Comp)	Comp Avg	Standardized	Comp F(T≤10)	System F(T≤10)	Comp F(T≤20)	System F(T≤20)	Comp F(T≤30)	System F(T≤30)	Comp F(T≤40)	System F(T≤40)	Comp F(T≤50)	System F(T≤50)
D30	D3060 Controls & Instrumentation	0.501	0.127	0.299	0.177	0.711	0.619	0.932	0.905	0.992	0.982	1.000	0.997
	D3040 Distribution Systems	0.484	0.123	0.236		0.684		0.920		0.983		0.997	
	D3090 Other HVAC Systems & Equipment	0.324	0.082	0.198		0.669		0.951		0.998		1.000	
	D3030 Cooling Generating Systems	0.575	0.146	0.154		0.641		0.947		0.998		1.000	
	D3050 Terminal & Package Units	0.584	0.148	0.152		0.597		0.892		0.982		0.998	
	D3070 Systems Testing & Balancing	0.517	0.131	0.147		0.630		0.945		0.998		1.000	
	D3010 Energy Supply	0.316	0.080	0.126		0.557		0.884		0.973		0.989	
	D3020 Heat Generating Systems	0.636	0.162	0.117		0.491		0.801		0.944		0.990	
		3.937											

Table 11: D40 Fire Protection System Probabilistic Model

	Component-Section (C-S)	C-S Wts	Standardized	C-S F(T≤10)	Comp F(T≤10)	C-S F(T≤20)	Comp F(T≤20)	C-S F(T≤30)	Comp F(T≤30)	C-S F(T≤40)	Comp F(T≤40)	C-S F(T≤50)	Comp F(T≤50)
D4010	D401001 Fire Alarm Distribution	1.000	0.735	0.147	0.147	0.630	0.630	0.945	0.945	0.998	0.998	1.000	1.000
	D401002 Fire Alarm Devices	0.361	0.265	0.147		0.630		0.945		0.998		1.000	
		1.361											
D4020	D402001 Fire Protection Water Piping & Equip	1.000	0.500	0.147	0.147	0.630	0.630	0.945	0.945	0.998	0.998	1.000	1.000
	D402002 Fire Pump	1.000	0.500	0.147		0.630		0.945		0.998		1.000	
		2.000											
D4030	D403001 Standpipe Equipment & Piping	0.211	1.000	0.147	0.147	0.630	0.630	0.945	0.945	0.998	0.998	1.000	1.000
		0.211											
D4040	D404002 Sprinkler Water Supply Equip & Piping	0.315	0.500	0.104	0.059	0.497	0.291	0.865	0.546	0.986	0.705	1.000	0.815
	D404001 Sprinklers & Releasing Devices	0.315	0.500	0.014		0.085		0.227		0.424		0.630	
		0.630											
D4050	D405001 Portable Extinguishers	1.000	1.000	0.147	0.147	0.630	0.630	0.945	0.945	0.998	0.998	1.000	1.000
		1.000											
D4090	D409002 Foam Generating Equipment	1.000	0.254	0.147	0.132	0.630	0.581	0.945	0.910	0.998	0.991	1.000	1.000
	D409003 Clean Agent Systems	1.000	0.254	0.147		0.630		0.945		0.998		1.000	
	D409090 Other Special Fire Protection Systems	1.000	0.254	0.147		0.630		0.945		0.998		1.000	
	D409004 Hood & Duct Fire Protection	0.470	0.119	0.085		0.424		0.800		0.968		0.998	
	D409001 Carbon Dioxide Systems	0.470	0.119	0.085		0.424		0.800		0.968		0.998	
		3.940											

	Component (Comp)	Comp Wts	Standardized	Comp F(T≤10)	System F(T≤10)	Comp F(T≤20)	System F(T≤20)	Comp F(T≤30)	System F(T≤30)	Comp F(T≤40)	System F(T≤40)	Comp F(T≤50)	System F(T≤50)
D40	D4020 Fire Supp Water Supply / Equip	0.346	0.188	0.147	0.132	0.630	0.574	0.945	0.882	0.998	0.954	1.000	0.973
	D4030 Standpipe Systems	0.343	0.186	0.147		0.630		0.945		0.998		1.000	
	D4050 Fire Protection Specialties	0.311	0.169	0.147		0.630		0.945		0.998		1.000	
	D4010 Fire Alarm & Detection Systems	0.307	0.167	0.147		0.630		0.945		0.998		1.000	
	D4090 Other Fire Protection Systems	0.268	0.145	0.132		0.581		0.910		0.991		1.000	
	D4040 Sprinklers	0.268	0.145	0.059		0.291		0.546		0.705		0.815	
		1.842											

Table 12: D50 Electrical System Probabilistic Model

	Component-Section (C-S)	C-S Wts	Standardized	C-S F(T≤10)	Comp F(T≤10)	C-S F(T≤20)	Comp F(T≤20)	C-S F(T≤30)	Comp F(T≤30)	C-S F(T≤40)	Comp F(T≤40)	C-S F(T≤50)	Comp F(T≤50)
D5010	D501001 Main Transformers	1.000	0.170	0.147		0.630		0.945		0.998		1.000	
	D501002 Service Entrance Equipment	1.000	0.170	0.147		0.630		0.945		0.998		1.000	
	D501090 Other Service & Distribution	1.000	0.170	0.085		0.424		0.800		0.968		0.998	
	D501003 Interior Distribution Transformers	0.485	0.083	0.053	0.076	0.289	0.349	0.630	0.612	0.881	0.763	0.978	0.861
	D501006 Motor Control Centers	0.384	0.065	0.025		0.147		0.372		0.630		0.833	
	D501004 Panelboards	1.000	0.170	0.014		0.085		0.227		0.424		0.630	
	D501005 Enclosed Circuit Breakers	1.000	0.170	0.014		0.085		0.227		0.424		0.630	
		5.869											
D5020	D502090 Other Lighting & Branch Wiring	0.430	0.445	0.289		0.881		0.998		1.000		1.000	
	D502002 Lighting Equipment	0.301	0.312	0.147	0.177	0.630	0.601	0.945	0.774	0.998	0.826	1.000	0.868
	D502001 Branch Wiring	0.236	0.244	0.009		0.053		0.147		0.289		0.459	
		0.967											
D5030	D503090 Other Communications & Alarms Systems	0.370	0.055	0.289		0.881		0.998		1.000		1.000	
	D503003 Intercommunications Systems	0.350	0.052	0.289		0.881		0.998		1.000		1.000	
	D503001 Telecommunications Systems	1.000	0.149	0.147		0.630		0.945		0.998		1.000	
	D503002 Public Address Systems	1.000	0.149	0.147	0.163	0.630	0.657	0.945	0.951	0.998	0.998	1.000	1.000
	D503004 Television Systems	1.000	0.149	0.147		0.630		0.945		0.998		1.000	
	D503005 Security Systems	1.000	0.149	0.147		0.630		0.945		0.998		1.000	
	D503006 Nurse Call Systems	1.000	0.149	0.147		0.630		0.945		0.998		1.000	
	D503007 Clock & Program Systems	1.000	0.149	0.147		0.630		0.945		0.998		1.000	
		6.720											
D5090	D509090 Other Special Systems & Devices	0.423	0.076	0.190		0.731		0.978		1.000		1.000	
	D509001 General Construction Items (Electrical)	1.000	0.180	0.147		0.630		0.945		0.998		1.000	
	D509002 Emergency Lighting & Power	1.000	0.180	0.147		0.630		0.945		0.998		1.000	
	D509005 Electric Heating	1.000	0.180	0.147	0.123	0.630	0.526	0.945	0.801	0.998	0.881	1.000	0.924
	D509006 Energy Management Control System	1.000	0.180	0.147		0.630		0.945		0.998		1.000	
	D509004 Lightning Protection	0.610	0.110	0.014		0.085		0.227		0.424		0.630	
	D509003 Grounding Systems	0.525	0.094	0.014		0.085		0.227		0.424		0.630	
		5.558											

	Component (Comp)	Comp Wts	Standardized	Comp F(T≤10)	System F(T≤10)	Comp F(T≤20)	System F(T≤20)	Comp F(T≤30)	System F(T≤30)	Comp F(T≤40)	System F(T≤40)	Comp F(T≤50)	System F(T≤50)
D50	D5030 Communications & Security	0.336	0.168	0.163		0.657		0.951		0.998		1.000	
	D5020 Lighting & Branch Wiring	0.671	0.336	0.177	0.133	0.601	0.519	0.774	0.760	0.826	0.846	0.868	0.899
	D5090 Other Electrical Services	0.383	0.191	0.123		0.526		0.801		0.881		0.924	
	D5010 Electrical Service & Distribution	0.609	0.305	0.076		0.349		0.612		0.763		0.861	
		1.999											

Model Validation

After the probabilistic model is created, it must be validated to determine its predictive ability. As previously discussed in Chapter III, the model was validated using real-world failure data by querying Civil Engineering Work Orders (WOs) from the Interim Work Information Management System (IWIMS). These WOs were obtained from an Air Force Base during the period of fiscal year 2013.

Work Order Database

The original WO data were reported and received in a text file format. To better organize and store the WO data as well as add the ability to efficiently conduct searches, the data were converted into an Oracle Database. However, before the data could be input into the database, the text file was converted to a comma separated value (CSV) file. This was because the text file was not a delimited file, meaning that there were no specific characters used to separate the values in the rows. Examples of such delimiters are the comma, tab, and colon.

The first step in creating the Oracle Database was to create the table used to store the data. This table was entitled “WORKORDERS” and was created using Structured Query Language (SQL), which is the programming language used to communicate with the database. The SQL source script used to create the table “WORKORDERS” can be found in Appendix E.

The next step was to load all of the data from the CSV file into the database. This was accomplished using the SQL*Loader. The resulting log file from the load can be found in Appendix F. As shown in Appendix F, there were a total of 7,685 rows of WO data that were loaded into the database. Once this data is loaded into the database, queries can be conducted to retrieve the pertinent data.

A query is used to retrieve the data based on certain criteria. As mentioned earlier, this research utilizes only emergency and urgent WOs to validate the model. Therefore, the query is written to only select the WOs where the column name of service type ("TYPESVS") is equal to emergency ("E") or urgent ("U"). In addition to the service type column, there is a column entitled work order indicator ("WOIND"), whose values range from A to Y. This research will only use the work order indicator "J" indicating direct scheduled work (DSW), which is any unscheduled repair. To simplify the database, these queries were accomplished through the use of a view so that the queries did not have to be repeated multiple times. The creation of this view can be seen in the SQL script found in Appendix G.

Once the WO data was filtered down to only the work orders that were DSW and emergency or urgent, the WOs can now be queried for failure in each of the systems in question: plumbing, HVAC, fire protection, and electrical. These queries were conducted by searching for key words in the WO title, such as "POWER" for the electrical system and "WATER" for the plumbing system. The SQL script for these queries can be found in Appendix G. Additionally, the resulting log file from these SQL queries can be found in Appendix H.

Assessing Work Orders

As mentioned previously, these queries were conducted to search for WOs where the title indicated complete system failure, not failure at the component or component-section level. Therefore, the results from the SQL queries must be filtered down even further. As seen in Appendix H, the SQL query for the electrical system returned 241 rows; however, after further evaluation, only 32 of these rows indicate complete electrical system failure. The SQL query for the HVAC system returned 79 rows, which was filtered down to 17 rows indicating complete HVAC system failure. Similarly, the SQL query for the fire protection system returned 97 rows, which was narrowed down to 27 rows, whereas the plumbing system SQL query returned 499 rows which was narrowed down to only 9 rows indicating complete plumbing system failure.

The total possible rows of WOs dealing strictly with system failure summed to 85. The next step in assessing these WOs was to attempt to find each of the system's inventory data in BUILDER™. The system inventory is needed so that the component-section data can be input into the probabilistic model to predict the system's probability of failure. These probabilities of failure will then be compared to the System Condition Index (SCI) that is automatically calculated and outputted into BUILDER™.

Even though there was a total of 85 possible system failures that could have been evaluated, there were only 23 usable system failures due to their completed inventory in BUILDER™. Figure 12 displays an example of the system inventory output from BUILDER™. The age was found by subtracting each component-section's year installed from 2014, since these WOs were submitted during fiscal year 2013. For systems that have multiple component-sections with different ages, the age for the component-section was found by taking the average of the various ages. The component-section ages were then input into the probabilistic model to produce the system's probability of failure as shown in Table 13.

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SMS **System Inventory Report**

Vandenberg Air Force Base (XUMUE)

01544 - SHOP							**VANDENBERG MAIN BASE SITE # 1 (XUMU0001)**
System	***Component***	***Section Description***	***Quantity (UM)***	***Yr. Installed***	***Yr Painted***		
D50 ELECTRICAL	D5010 ELECTRICAL SERVICE & DISTRIBUTION	PANEL | SWBD D501004 PANELBOARDS Main lugs, 200 amp	1 (EA)	1958	56		
	D5010 ELECTRICAL SERVICE & DISTRIBUTION	SWITCH | 480 REC D501004 PANELBOARDS Safety Switch, 30-100 Amp	1 (EA)	1990	24		
	D5010 ELECTRICAL SERVICE & DISTRIBUTION	SWITCH | 480 REC(2) D501004 PANELBOARDS Safety Switch, 30-100 Amp	1 (EA)	1990	24		
	D5010 ELECTRICAL SERVICE & DISTRIBUTION	SWITCH | EXT D501004 PANELBOARDS Safety Switch, 30-100 Amp	1 (EA)	1990	24		
	D5010 ELECTRICAL SERVICE & DISTRIBUTION	SWITCH | PNL A D501004 PANELBOARDS Safety Switch, 30-100 Amp	1 (EA)	1990	24	27.55	
	D5010 ELECTRICAL SERVICE & DISTRIBUTION	SWITCH | PNL B D501004 PANELBOARDS Safety Switch, 30-100 Amp	1 (EA)	1990	24		
	D5010 ELECTRICAL SERVICE & DISTRIBUTION	SWITCH | PNL C FEED D501004 PANELBOARDS Safety Switch, 30-100 Amp	1 (EA)	1990	24		
	D5010 ELECTRICAL SERVICE & DISTRIBUTION	SWITCH | RF RI D501004 PANELBOARDS Safety Switch, 30-100 Amp	1 (EA)	1990	24		
	D5010 ELECTRICAL SERVICE & DISTRIBUTION	SWITCH | RF RM D501004 PANELBOARDS Safety Switch, 30-100 Amp	1 (EA)	1990	24		
	D5020 LIGHTING & BRANCH WIRING	NA-291 D502002 LIGHTING EQUIPMENT Interior Lighting, FL - 3 Lamp T8	58 (EA)	2005	9	9	
	D5020 LIGHTING & BRANCH WIRING	NA-292 D502002 LIGHTING EQUIPMENT Interior Lighting, FL - 4 Lamp T8	18 (EA)	2005	9		
	D5030 COMMUNICATIONS & SECURITY	CCTV | PANEL D503005 SECURITY SYSTEMS General	1 (EA)	2005	9	9	
	D5030 COMMUNICATIONS & SECURITY	TELE / LAN | 1FL OFFICE D503001 TELECOMMUNICATIONS SYSTEMS General	1 (EA)	1995	19		
	D5030 COMMUNICATIONS & SECURITY	TELE / LAN | 2FL OFFICE D503001 TELECOMMUNICATIONS SYSTEMS General	1 (EA)	1995	19		
	D5030 COMMUNICATIONS & SECURITY	TELE / LAN | ELEC RM D503001 TELECOMMUNICATIONS SYSTEMS General	1 (EA)	1995	19	15.25	
	D5030 COMMUNICATIONS & SECURITY	TELE / LAN | RM204 D503001 TELECOMMUNICATIONS SYSTEMS General	1 (EA)	2010	4		
	D5090 OTHER ELECTRICAL SERVICES	D509004 LIGHTNING PROTECTION General	1 (EA)	1958	56	56	

Figure 12: Building 1544 Electrical System Inventory Report

Table 13: Probabilistic Model for Building 1544 Electrical System

Component-Section (Component-Section)	C-S Wts	Standardized	Age (years)	C-S F(T≤t)	Comp F(T≤t)
D501004 Panelboards	1.000	1.000	27.55	0.186	0.186
	1.000				
D502002 Lighting Equipment	0.301	1.000	9	0.114	0.114
	0.301				
D503001 Telecommunications Systems	1.000	0.500	15.25	0.385	0.249
D503005 Security Systems	1.000	0.500	9	0.114	
	2.000				
D509004 Lightning Protection	0.610	1.000	56	0.738	0.738
	0.610				

Component (Comp)	Comp Wts	Standardized	Comp F(T≤t)	System F(T≤t)
D5010 Electrical Service & Distribution	0.609	0.305	0.186	0.278
D5020 Lighting & Branch Wiring	0.671	0.336	0.114	
D5030 Communications & Security	0.336	0.168	0.249	
D5090 Other Electrical Services	0.383	0.191	0.738	
	1.999			

As previously mentioned, there were a total of 23 system failures evaluated in an effort to validate this model. These 23 system failures consisted of 8 electrical system failures, 8 HVAC system failures, 2 fire protection system failures, and 5 plumbing system failures. These 23 system failures, as well as each failed system's respective WO information, are outlined in Figure 13. Figure 13 also displays each failed system's probability of failure (PoF) computed by the probabilistic model, as well as the System Condition Index (SCI) computed by BUILDER™.

The PoF and SCI values were both assessed using a three-tiered scale of green, amber, and red ratings, but noting the tiers are defined differently. The SCI scale is a similar but condensed version of the Condition Index definitions found in Table 4. The main difference is that the failed tier of the SCI scale begins at 37 instead of 55, as 37 is the CI terminal value that was used in the probability of failure calculation shown in Equation 15. The PoF scale is then the inverse of the SCI scale and on a scale from 0.00 to 1.00, instead of on a scale from 0 to 100.

For the 23 system failures evaluated, the analysis in Figure 13 shows that the probability of failure categorization was as such: 2 green, 15 amber, and 6 red. The SCI categorization told a much different story in that 20 were green, 1 was amber, and 2 were red. In addition to assessing failed systems, a random sample of systems that had not failed was also assessed. The sample size was kept constant across the 4 system types: 8 from electrical, 8 from HVAC, 2 from fire protection, and 5 from plumbing. An attempt was also made to keep the SCI values constant between the failed and not failed systems.

Electrical System						
FAC#	WOTITLE	DATE	TYPESVS	WOIND	PoF	SCI
525	POWER LOSS	141114	U	J	0.64	92
763	NO POWER	140923	E	J	0.22	93
1544	EMERGENCY LIGHTS/ NO POWER	140127	U	J	0.28	90
1639	NO POWER	141014	U	J	0.18	91
5500	NO POWER	141006	U	J	0.34	90
6510	POWER OUTAGE	140423	E	J	0.23	92
7011	LOSS OF POWER	131230	E	J	0.39	93
8500	LOST ELECTRICAL POWER	140703	U	J	0.17	93

HVAC System						
FAC#	WOTITLE	DATE	TYPESVS	WOIND	PoF	SCI
7011	A/C NOT WORKING	140312	U	J	0.76	91
7015	A/C UNIT STOPPED WORKING	140825	E	J	0.70	93
7025	HVAC IS DOWN	140818	E	J	0.23	93
8195	HVAC UNIT DOWN	141110	E	J	0.21	91
8500	REPAIR A/C UNITS INOP	140916	U	J	0.33	87
10130	HVAC NOT WORKING	130925	U	J	0.05	93
10660	HVAC NOT WORKING	140206	U	J	0.53	89
12000	REPAIR INOP. HVAC	140728	U	J	0.26	85

Fire Protection System						
FAC#	WOTITLE	DATE	TYPESVS	WOIND	PoF	SCI
10577	FIRE ALARM PANEL	140821	E	J	0.93	0
16200	FIRE ALARM PANEL	141201	U	J	0.61	8

Plumbing System						
FAC#	WOTITLE	DATE	TYPESVS	WOIND	PoF	SCI
660	NO WATER IN FACILITY	131009	U	J	0.66	94
875	NO WATER IN BUILDING	140729	U	J	0.49	92
11041	NO WATER TO HALF OF BLDG RIGHT	140428	U	J	0.77	94
13330	NO WATER IN FACILITY	140220	E	J	0.01	91
16200	NO WATER/TOILETS NOT FLUSHING	140806	U	J	0.36	94

LEGEND

	SCI		PoF
Good	100-86	Green	0.00-0.14
Satisfactory/Poor	85-38	Amber	0.15-0.62
Failed	37-0	Red	0.63-1.00

Figure 13: Analysis of Failed Building Systems

Electrical System		
FAC#	PoF	SCI
799	0.43	92
14300	0.28	93
13321	0.30	90
7015	0.37	91
9360	0.39	90
7050	0.43	92
9190	0.48	93
11248	0.15	93

HVAC System		
FAC#	PoF	SCI
16170	0.48	91
23201	0.26	93
12006	0.03	93
13323	0.23	91
9320	0.38	87
1508	0.40	93
14400	0.10	89
7425	0.31	85

Fire Protection System		
FAC#	PoF	SCI
475	0.99	6
8337	0.66	10

Plumbing System		
FAC#	PoF	SCI
1338	0.29	94
10122	0.43	92
1810	0.09	94
9190	0.44	91
907	0.19	94

LEGEND

SCI		PoF
100-86	Green	0.00-0.14
85-38	Amber	0.15-0.62
37-0	Red	0.63-1.00

Figure 14: Analysis of Not Failed Building Systems

As the analysis in Figure 14 shows, the probability of failure categorization of the systems that had not failed was: 3 green, 18 amber, and 2 red. The SCI categorization of the not failed systems was the same as the SCI categorization of the failed systems in that 20 were green, 1 was amber, and 2 were red. As previously mentioned, the intent for assessing systems that had not failed was for resulting probabilities of failure to be lower than the probabilities of failure in the failed systems.

Contingency Analysis

Rather than analyzing the specific probabilities of failure values, which are continuous variables, we are only interested in analyzing whether or not the model predicted that the system would fail or would not fail, which are nominal variables. The method to test if these nominal variables are related is through contingency analysis. One tool of contingency analysis is the contingency table which provides a summary of two or more nominal variables. The statistical program that is used to produce these contingency tables is JMP® 10.

The first contingency table compared the categorization of the green, amber, and red ratings of both the failed and not failed systems from both the PoF and SCI models. This contingency table, found in Table 14, is known as a three-way table because it summarizes three nominal variables. The main information to be concerned with in this table is to examine if the PoF and SCI models are producing the same predictions. This information is garnered from the bolded and colored cells in Table 14. These cells indicate that the agreement between the SCI and the PoF models is low since the categorizations matched only 10 times out of the 46 samples.

Table 14: SCI vs. PoF Contingency Table

		SCI			
	Observed	G	A	R	Row Total
PoF	G	**5**	0	0	5
	A	30	**2**	1	33
	R	5	0	**3**	8
	Column Total	40	2	4	46

Next, the SCI and PoF models were evaluated separately for their respective predictive ability. Since the purpose of the SCI and PoF models is to predict system failure, the nominal variables were narrowed down from green, amber, and red to fail and no fail. The green and amber ratings comprise the no fail variable, and the red rating comprises the fail variable. These two variables can then be compared with the truth of whether or not the system failed or did not fail in the real world. There are only two variables, so this contingency table is known as a two-way table, or a 2x2 table.

The predictive ability of the SCI model is assessed. The predictions from the SCI model are compared with the truth, and these results are displayed in the contingency table found in Table 15. As with the first contingency table, the main information to be garnered is from the bolded and colored cells. These cells show that the SCI method predicted the system to fail when in truth it did fail 2 times, and it predicted the system not to fail when in truth it did not fail 21 times.

Table 15: SCI Predicted vs. Truth Contingency Table and Test Outputs

		SCI Predicted		
	Observed Expected	Fail	No Fail	Row Total
Truth	Fail	2 2	21 21	23
	No Fail	2 2	21 21	23
	Column Total	4	42	46

Test	**ChiSquare**	**Prob>ChiSq**
Likelihood Ratio	0.000	1.0000
Pearson	0.000	1.0000

Along with the contingency table, Table 15 also displays the statistical test outputs. The purpose of these tests is to test whether or not these variables are independent. The Chi Square test is used to test for independence, and two of these Chi Square tests include the Likelihood Ratio and Pearson tests. In general, the p-value that is found from the Pearson test under the header of Prob>ChiSq is used (Schlotzhauer, 2007:422). The Pearson test uses the observed cell frequencies and compares them with the expected cell frequencies, whereas the Likelihood Ratio test uses a more complex formula (Schlotzhauer, 2007:420).

The expected cell frequencies are calculated by multiplying the row total and the column total, and dividing by the total number of observations (Schlotzhauer, 2007:424). For example, for the Fail-Fail cell in Table 15, the expected cell frequency is found by the following equation:

$$\begin{aligned} Expected\ \ Count &= \frac{\left[(row\,total\ \ for\ Fail)\times(column\,total\ \ for\ Fail)\right]}{total\ N} \\ &= \frac{(23\times 4)}{46} = 2 \end{aligned} \tag{22}$$

As seen from the bolded and colored cells in Table 15, the observed frequencies and expected frequencies were the same for all of the cells. For this reason, the p-value computed from the Pearson test resulted in a value of 1.00. The p-value is then compared to the significance level, α, which in this research is 0.10. Since the p-value is much greater than the significance level, the SCI model predictions and the truth of whether or not the system failed are statistically independent and therefore this analysis concludes that the SCI model has no predictive ability.

The predictive ability of the PoF model is assessed next. Table 16 displays the resulting contingency table where the predictions from the PoF model are compared with the truth. As with the previous contingency tables, the main information to be garnered is found in the bolded and colored cells. This table yields that 6 times the PoF model predicted the system to fail when in truth it did fail, and 21 times the PoF model predicted the system not to fail when in truth it did not fail.

Table 16: PoF Predicted vs. Truth Contingency Table and Test Outputs

		PoF Predicted		
	Observed Expected	Fail	No Fail	Row Total
Truth	Fail	6 4	17 19	23
	No Fail	2 4	21 19	23
	Column Total	8	38	46

Test	**ChiSquare**	**Prob>ChiSq**
Likelihood Ratio	2.515	0.1128
Pearson	2.421	0.1197

As before, the p-value is then compared to the significance level of 0.10. According to Table 16, the p-value calculated from the Pearson test was found to be 0.12. This value is slightly greater than the significance level. It is therefore concluded that there is not enough evidence to reject that the variables are independent at a significance level of 0.10. In other words, because of the pre-defined significance level of 0.10, the contingency analysis concludes that there is not enough evidence to claim that the variables are dependent. However, another interpretation of the p-value is that there is a 12% probability that the results of the model are due to random chance. This interpretation then allows for a fair amount of dependency between the variables, and much more dependency than the SCI model. Overall, this research concludes that there is statistical evidence that the PoF model has much more predictive ability than the SCI model.

Summary

This chapter provided the analysis and results from this research effort. The main results presented in this chapter are the probabilistic models for the plumbing, HVAC, fire protection, and electrical systems. Next, it is concluded during the model validation step that the probabilistic models achieved a higher predictive ability than the BUILDER™ SCI model. This conclusion was achieved through the use of contingency analysis, more specifically through the use of contingency tables.

V. Discussion and Conclusion

Chapter Overview

This chapter provides a review of the research that was conducted and answers the research questions that were proposed in Chapter I. It discusses the development of the probabilistic model as a tool to identify risks in a system. Additionally, an evaluation of the model's strength and limitations are presented as well as the recommendations for future research in this area.

Review of Research Questions

Typically, probabilistic risk assessments are only conducted in the chemical and nuclear industries or in agencies that deal with complex technological entities such as the National Aeronautics and Space Administration (NASA) (Stamatelatos, 2000). Risk assessment has classically been defined by three questions (Kaplan & Garrick, 1981):

- What can go wrong?
- What is the likelihood that it could go wrong?
- What are the consequences of failure?

Therefore, the research questions posed in this research are closely related to the questions posed during a risk assessment.

1. **What are the probabilities of failure of the component-sections comprising the system and/or building?**

The probabilities of failure of the component-sections were found through the use of the Weibull distribution and more specifically through the use of the formula displayed in Equation 15. The probability of failure is thus a function of the initial reliability, the

Condition Index (CI) at failure, the normalized age, as well as the service life adjustment and reliability degradation parameters. In the methodology for analyzing fault trees with fuzzy logic, the probabilities were represented in the probabilities vector, *B*. The probabilities of failure values for the ages of 10, 20, 30, 40, and 50 years are displayed in the probabilistic models of the four systems investigated and can be found in Tables 9, 10, 11, and 12.

2. What are the consequences of failure of the component-sections comprising the system and/or building?

The consequences of failure of the component-sections are found through the use of subcomponent weight factors. The subcomponent weight factors indicate the relative importance of each subcomponent in terms of the cost to replace and the importance or criticality to the overall component (USACE, 2014a). In the methodology for analyzing fault trees with fuzzy logic, the consequences were represented in the weighting vector, *W*. The consequence of failure values the component-sections are displayed in the probabilistic models of the four systems investigated and are found in Tables 9,10, 11, and 12.

3. If a system fails, what is the probability that the failure can be attributed to a specific component-section?

Since the probabilistic model predicts the probability of failure at the higher level by aggregating the probabilities and consequences of the lower level, the Probability of Failure (PoF) of a system is a function of all the probabilities of failure of the component-sections that make up that system. For this reason the probabilistic model was built to show each of the individual component-section's probabilities of failure. If a system fails, the probabilistic model for that system can be referenced to obtain the probabilities of failure for each of the component-sections, and the component-section with the highest probability of failure will likely have contributed the most towards the system failure.

4. Can a model be created to predict the probability of failure at the component-section, component, and system levels?

Yes, a model can be created to predict the probability of failure at the component-section, component, and system levels. The models for the plumbing, HVAC, fire protection, and electrical systems found in Tables 9, 10, 11, and 12, respectively, display the probabilities of failure at each of the hierarchy levels. These models calculate the probability of failure at the component-section using the Weibull distribution and then weight the probability by the consequence of failure to "roll up" the probabilities of failure to the next highest level.

Model Strengths

The foundation on which this probabilistic model is built is on the concept of risk. Risk is the chance of something happening that will have an impact on objectives, and it is a function of both the probabilitiy of failure and the consequence of failure (Standards Australia/Standards New Zealand, 2004:3,49). This model is an objective and standardized method to determine the probabilities of failure because it uses inventory data such as the age of the component-sections, unlike the System Condition Index (SCI) model which uses condition assessment data to compute the Condition Index.

In addition to condition assessment data, the SCI model rolls up the CI by using the current replacement value (CRV) as a metric, as previously displayed in Figure 2. By defining each subsequent index in this way, the replacement value of each unit (whether component or component-section) imparts significant influence on the resulting index calculated for each level. This implies that component-sections or components which cost more are more important and therefore have a greater impact on the overall SCI.

This concept is depicted in Table 17. Building off of the previous example of building 1544's electrical system used in Table 13, which portrayed the results of the PoF model, Table 17 delves into the results of the SCI model as calculated in BUILDER™. This table substantiates the previous concept that components which cost more are considered more important according to this model because they have a greater impact on the overall SCI. The D5030 Communications & Security component has the highest component replacement value (CRV) of all the components and subsequently weights a value of 51 into the SCI of 90. Thus, the issue is raised of whether or not this component is truly the most important component comprising the system. This issue is explored in detail in the white paper found in Appendix I.

Table 17: SCI Model for Building 1544 Electrical System

Component (Comp)	Comp CRV	Weighted Comp CRV	BCCI	Weighted SCI
		= Comp CRV / System CRV		= Weighted Comp CRV * BCCI
D5010 Electrical Service & Distribution	$11,120	0.074	63	5
D5020 Lighting & Branch Wiring	$57,500	0.380	92	35
D5030 Communications & Security	$82,500	0.545	93	51
D5090 Other Electrical Services	$130	0.001	87	0
System CRV	$151,250		***SCI***	90

To combat the aforementioned issue of distinguishing importance, the PoF model employs the consequence of failure values to signify importance. Table 13, presented previously, displays the PoF model for the electrical system of building 1544. In this table, it is gathered that the consequence of failure values, or component weights, are more equally distributed among the components, unlike the weights of the component's CRV in Table 17. Additionally, the PoF model's consequence of failure values remain constant from system to system, with only the standardized weights changing depending on which component-sections and components make up the system. This is not the case for the SCI model, as the importance values vary between systems because they are dependent upon the CRV values of the component-sections and components that comprise the system. This further contributes to the argument that the PoF model is a more objective and standardized method to determine the probabilities of failure of building systems.

Table 13: Probabilistic Model for Building 1544 Electrical System

Component (Comp)	Comp Wts	Standardized	Comp F(T≤t)	System F(T≤t)
D5010 Electrical Service & Distribution	0.609	0.305	0.186	0.278
D5020 Lighting & Branch Wiring	0.671	0.336	0.114	
D5030 Communications & Security	0.336	0.168	0.249	
D5090 Other Electrical Services	0.383	0.191	0.738	
SUM	1.999			

Another strength of the probabilistic model is the ability to assess the probability of failure and consequence of failure values separately or together to understand the relationship between risk and its factors. This relationship is illustrated by means of a simple matrix. To paraphrase Labi (2013), a risk matrix can help the system owner visualize the risks and communicate issues relating to risk because they are easy to understand and construct.

An example risk matrix is shown in Figure 15. This risk matrix was created using the component information from Table 13. It should be noted that the consequence of failure values were derived from the non-standardized component weights. One important aspect of the creation of risk matrices is the categorization levels of the probability and consequence. In Figure 15, the categorization levels for both the probabilitiy and consequence were set at a value of 0.5, which was chosen for ease of visualization, not for any certain significance. If the system owner intends to use the risk matrix to establish priorities for resource allocations, the categorization levels should be carefully placed to account for whether or not the organization is willing to accept risk (risk seeking) or is more conservative (risk averse).

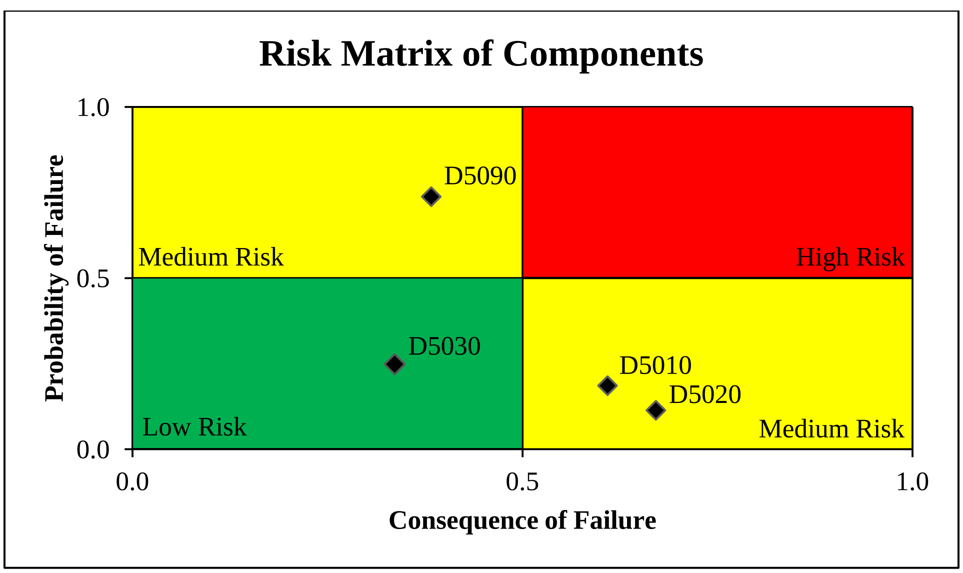

Figure 15: Risk Matrix for Building 1544 Electrical System

Figure 15 displays a 2x2 risk matrix with four possibilities and three risk levels. These possibilities and risk levels are:

- Low probability of failure, low consequence of failure – Low Risk
- High probability of failure, low consequence of failure – Medium Risk
- Low probability of failure, high consequence of failure – Medium Risk
- High probability of failure, high consequence of failure – High Risk

From the example components given in Table 13, the risk matrix determined that one component (D5030) was low risk and the remaining three components (D5010, D5020, and D5090) were medium risk. Risk matrices are not limited to a 2x2 configuration; the axes may be further divided to produce more detailed categorization levels. The number of divisions along each axis will be determined by the level of detail and the nature of the measures, as well as the context, scope, resources and use to which the output will be used (Standards Australia/Standards New Zealand, 2004).

Model Limitations

The primary limitation of this PoF model is that the probability of failure at the component-section level considers age as the only factor. In reality, failure is not just age-based; it is dependent upon multiple factors. One such factor is condition. It has been argued that failure is also dependent upon factors such as levels of service and lost opportunities (Martin, 2014). Additionally, Grussing et al. (2014) state that age alone is not always the significant predictor of condition loss. There are several other factors that can affect a component’s current condition and its change over time such as environmental exposure, use and abuse, and maintenance and repair received (Grussing et al., 2014). BUILDER™ currently accounts for condition in its SCI calculations; applying a similar accounting for condition to the PoF calculations will strengthen the model.

Recommendations for Future Work

As previously mentioned while determining what BUILDER™ defines as failure, it was realized that the CI levels are subjective because they vary by which definitions and scales are used. A research study could be conducted to attempt to validate or optimize the CI levels. This study could explore real-world failure data to determine at what level building systems, components, and even component-sections fail. These levels could then be optimized, attempting to capture as many real-world failures as possible, while lessening the amount that had not failed.

Another recommendation for future work, which was proposed by Grussing (2014a), explores accuracy of the Component Importance Index (CII) values. The data for the CII values were gathered prior to BUILDER™ adopting the UNIFORMAT II naming convention. Also, the CII values were based on some preliminary surveys of perceived component importance, but with a small number of respondents and a wide range of variability of responses in some cases. It is unknown whether or not these values are statistically significant. In order to evaluate whether or not these values are statistically significant or to propose new values, a formal study could be conducted with a large number of respondents.

Conclusions

The purpose of this research was to develop a probabilistic model which predicts the probability of failure at the system level of building infrastructure hierarchy. These models were created on the basis of risk by weighting the probabilities of failure by the consequences of failure to determine the expected probability of failure of the systems. These models were then validated using real-world Air Force work order data to find conclude that the probabilistic failure models provided higher predictive ability compared to the BUILDER™ SCI model, as well as provided an objective and standardized process.

Appendix A. UNIFORMAT II Classification for Building Elements (Adapted from Charette & Marshall, 1999)

Level 1 Major Group Elements	Level 2 Group Elements	Level 3 Individual Elements
A SUBSTRUCTURE	A10 Foundations	A1010 Standard Foundations
		A1020 Special Foundations
		A1030 Slab on Grade
	A20 Basement Construction	A2010 Basement Excavation
		A2020 Basement Walls
B SHELL	B10 Superstructure	B1010 Floor Construction
		B1020 Roof Construction
	B20 Exterior Enclosure	B2010 Exterior Walls
		B2020 Exterior Windows
		B2030 Exterior Doors
	B30 Roofing	B3010 Roof Coverings
		B3020 Roof Openings
C INTERIORS	C10 Interior Construction	C1010 Partitions
		C1020 Interior Doors
		C1030 Fittings
	C20 Stairs	C2010 Stair Construction
		C2020 Stair Finishes
	C30 Interior Finishes	C3010 Wall Finishes
		C3020 Floor Finishes
		C3030 Ceiling Finishes
D SERVICES	D10 Conveying	D1010 Elevators & Lifts
		D1020 Escalators & Moving Walks
		D1090 Other Conveying Systems
	D20 Plumbing	D2010 Plumbing Fixtures
		D2020 Domestic Water Distribution
		D2030 Sanitary Waste
		D2040 Rain Water Drainage
		D2090 Other Plumbing Systems
	D30 HVAC	D3010 Energy Supply
		D3020 Heat Generating Systems
		D3030 Cooling Generating Systems
		D3040 Distribution Systems
		D3050 Terminal & Package Units
		D3060 Controls & Instrumentation
		D3070 Systems Testing & Balancing
		D3090 Other HVAC Systems & Equipment
	D40 Fire Protection	D4010 Sprinklers
		D4020 Standpipes
		D4030 Fire Protection Specialties
		D4090 Other Fire Protection Systems
	D50 Electrical	D5010 Electrical Service & Distribution
		D5020 Lighting and Branch Wiring
		D5030 Communications & Security
		D5090 Other Electrical Systems
E EQUIPMENT & FURNISHINGS	E10 Equipment	E1010 Commercial Equipment
		E1020 Institutional Equipment
		E1030 Vehicular Equipment
		E1090 Other Equipment
	E20 Furnishings	E2010 Fixed Furnishings
		E2020 Movable Furnishings
F SPECIAL CONSTRUCTION & DEMOLITION	F10 Special Construction	F1010 Special Structures
		F1020 Integrated Construction
		F1030 Special Construction Systems
		F1040 Special Facilities
		F1050 Special Controls and Instrumentation
	F20 Selective Building Demolition	F2010 Building Elements Demolition
		F2020 Hazardous Components Abatement

Appendix B. Original Component Importance Index Values (Adapted from Grussing, 2014a)

System	Component	CII Values Average
Plumbing	Other Plumbing Equipment	0.303
	Piping	0.690
	Plumbing Fixtures	0.541
	Septic Tank	0.566
	Sump	0.353
	Water Softener/Water Heater/ Heat Exchanger/Etc	0.394
	Well	0.544
HVAC	Air Handling/Ductwork	0.486
	Control System	0.517
	Cooling and Heating Unit	0.584
	Cooling Unit/Plant	0.575
	Dehumidifier/Desiccator	0.359
	Fuel Storage	0.547
	Heating Unit/Plant	0.636
	Humidity Equipment	0.457
	Other HVAC Equipment	0.324
	Pump/Compressor/Piping	0.531
	Solar Water Heating Unit	0.204
	Thermal Storage Unit	0.197
	Ventilation/Exhaust Equipment	0.506
Fire Suppression	Backflow Preventor	0.259
	Fire Extinguishing	0.311
	Fire Suppression	0.496
	Fire/Smoke Alarm	0.307
	Jockey Pump	0.245
	Piping (Fire Suppression)	0.309
	Pump (Fire Suppression)	0.320
	Water Treatment (Fire Supp)	0.268
Electrical	Distribution	0.760
	Electrical Service Distribution	0.760
	Generator Set	0.434
	Grounding	0.406
	Intercom	0.233
	Intruder Detection/Security	0.439
	Lightning Protection	0.256
	Lightning System	0.582
	Panels	0.753
	Transfer Switch	0.418
	Transformers	0.506
	Uninterruptible Power Supply	0.434

Appendix C. Original Components to UNIFORMAT II Components (Adapted from Grussing, 2014a)

System	Original Component	UNIFORMAT II Component
D20 Plumbing	Plumbing Fixtures	D2010 Plumbing Fixtures
	Sump	D2010 Plumbing Fixtures D2040 Rain Water Drainage
	Piping	D2020 Domestic Water Distribution D2030 Sanitary Waste D2040 Rain Water Drainage
	Water Softener/Water Heater/ Heat Exchanger/Etc	D2020 Domestic Water Distribution
	Other Plumbing Equipment	D2090 Other Plumbing Systems
	Well	
	Septic Tank	D2030 Sanitary Waste
D30 HVAC	Solar Water Heating Unit	D3010 Energy Supply
	Thermal Storage Unit	D3010 Energy Supply
	Fuel Storage	D3010 Energy Supply
	Heating Unit/Plant	D3020 Heat Generating Systems
	Cooling Unit/Plant	D3030 Cooling Generating Systems
	Dehumidifier/Desiccator	D3040 Distribution Systems
	Ventilation/Exhaust Equipment	D3040 Distribution Systems
	Air Handling/Ductwork	D3040 Distribution Systems
	Cooling and Heating Unit	D3040 Distribution Systems D3050 Terminal & Package Units
	Control System	D3060 Controls & Instrumentation D3070 Systems Testing & Balancing
	Humidity Equipment	D3060 Controls & Instrumentation
	Other HVAC Equipment	D3090 Other HVAC Systems & Equip
	Pump/Compressor/Piping	D3060 Controls & Instrumentation
D40 Fire Protection	Fire/Smoke Alarm	D4010 Fire Alarm & Detection Systems
	Backflow Preventor	D4020 Fire Supp Water Supply / Equip
	Fire Suppression	D4020 Fire Supp Water Supply / Equip D4030 Standpipe Systems
	Jockey Pump	D4030 Standpipe Systems
	Piping (Fire Suppression)	D4020 Fire Supp Water Supply / Equip D4030 Standpipe Systems
	Pump (Fire Suppression)	D4020 Fire Supp Water Supply / Equip D4030 Standpipe Systems
	Fire Extinguishing	D4050 Fire Protection Specialties
	Water Treatment (Fire Supp)	D4040 Sprinklers D4090 Other Fire Protection Systems

System	Original Component	UNIFORMAT II Component
D50 Electrical	Distribution	D5010 Electrical Service & Distribution
	Panels	D5010 Electrical Service & Distribution
	Transfer Switch	D5010 Electrical Service & Distribution
	Transformers	D5010 Electrical Service & Distribution
	Lighting System	D5020 Lighting & Branch Wiring
	Electrical Service Distribution	D5020 Lighting & Branch Wiring
	Intercom	D5030 Communications & Security
	Intruder Detection/Security	D5030 Communications & Security
	Generator Set	D5090 Other Electrical Services
	Grounding	D5090 Other Electrical Services
	Lightning Protection	D5090 Other Electrical Services
	Uninterruptible Power Supply	D5090 Other Electrical Services

Appendix D. UNIFORMAT II Coded Component Importance Index Values (Adapted from Grussing, 2014a)

System	UNIFORMAT II Component	CII Values Average
D20 Plumbing	D2010 Plumbing Fixtures	0.447
	D2020 Domestic Water Distribution	0.542
	D2030 Sanitary Waste	0.628
	D2040 Rain Water Drainage	0.522
	D2090 Other Plumbing Systems	0.303
D30 HVAC	D3010 Energy Supply	0.316
	D3020 Heat Generating Systems	0.636
	D3030 Cooling Generating Systems	0.575
	D3040 Distribution Systems	0.484
	D3050 Terminal & Package Units	0.584
	D3060 Controls & Instrumentation	0.501
	D3070 Systems Testing & Balancing	0.517
	D3090 Other HVAC Systems And Equipment	0.324
D40 Fire Protection	D4010 Fire Alarm And Detection Systems	0.307
	D4020 Fire Supp Water Supply / Equip	0.346
	D4030 Standpipe Systems	0.343
	D4040 Sprinklers	0.268
	D4050 Fire Protection Specialties	0.311
	D4090 Other Fire Protection Systems	0.268
D50 Electrical	D5010 Electrical Service & Distribution	0.609
	D5020 Lighting & Branch Wiring	0.671
	D5030 Communications & Security	0.336
	D5090 Other Electrical Services	0.383

Appendix E. SQL Source Script

```
spool ImportLog.log

REM Set environmental variables
SET ECHO ON
SET HEADING ON
SET NEWPAGE NONE
SET LINESIZE 300
SET FEEDBACK ON
SET COLSEP '|'
SET TIMING ON

REM Nuke tables if they exist
DROP TABLE WORKORDERS CASCADE CONSTRAINTS;

REM Create WORKORDERS Table
CREATE TABLE WORKORDERS
    ( WOKEY             VARCHAR2(20)
    , FACIDNR           VARCHAR2(10)
    , WOTITLE           VARCHAR2(35)
    , CREATEDATE        VARCHAR2(10)
    , TYPESVS           VARCHAR2(7)
    , WOIND             VARCHAR2(7)
    ) ;

spool off;

exit;
```

Appendix F. SQL*Loader Resulting Log File

```
SQL*Loader: Release 11.2.0.2.0 - Production on Tue Dec 30 11:33:23 2014

Copyright (c) 1982, 2009, Oracle and/or its affiliates.  All rights
reserved.

Control File:   loadworkorders.ctl
Data File:      C:\Documents and Settings\AllUsers\Documents\
WorkOrders.csv
  Bad File:     WorkOrders.bad
  Discard File:  none specified

 (Allow all discards)

Number to load: ALL
Number to skip: 0
Errors allowed: 50
Bind array:     64 rows, maximum of 256000 bytes
Continuation:    none specified
Path used:      Conventional

Table WORKORDERS, loaded from every logical record.
Insert option in effect for this table: INSERT


   Column Name               Position   Len  Term Encl Datatype

-------------------------- ---------- ----- ---- ---- -----------------
WOKEY                           FIRST     *   ,  O(") CHARACTER
FACIDNR                          NEXT     *   ,  O(") CHARACTER
WOTITLE                          NEXT     *   ,  O(") CHARACTER
CREATEDATE                       NEXT     *   ,  O(") CHARACTER
TYPESVS                          NEXT     *   ,  O(") CHARACTER
WOIND                            NEXT     *   ,  O(") CHARACTER


Table WORKORDERS:
  7685 Rows successfully loaded.
  0 Rows not loaded due to data errors.
  0 Rows not loaded because all WHEN clauses were failed.
  0 Rows not loaded because all fields were null.


Space allocated for bind array:                  99072 bytes(64 rows)
Read   buffer bytes: 1048576

Total logical records skipped:          0
Total logical records read:          7685
Total logical records rejected:         0
Total logical records discarded:        0

Run began on Tue Dec 30 11:33:23 2014
Run ended on Tue Dec 30 11:33:24 2014

Elapsed time was:     00:00:00.78
CPU time was:         00:00:00.13
```

Appendix G. SQL Queries Script

```
spool WOQUERYRESULTS.log


REM Set environmental variables
SET ECHO ON
SET HEADING ON
SET PAGESIZE 50000
SET NEWPAGE NONE
SET LINESIZE 300
SET FEEDBACK ON
SET COLSEP '|'

REM Nuke view if it exists
DROP VIEW WOS_EMER_URG

REM Create WOS_EMER_URG View
CREATE VIEW WOS_EMER_URG AS
SELECT FACIDNR, WOTITLE, CREATEDATE, TYPESVS, WOIND
FROM WORKORDERS
WHERE (WOIND='J' AND TYPESVS='E' OR TYPESVS='U')
ORDER BY TYPESVS;

REM SELECT * FROM WOS_EMER_URG;

REM Electrical System
SELECT * FROM WOS_EMER_URG
WHERE (WOTITLE LIKE '%POWER%' OR WOTITLE LIKE '%ELEC%')
ORDER BY TYPESVS;

REM HVAC System
SELECT * FROM WOS_EMER_URG
WHERE (WOTITLE LIKE '%A/C%' OR WOTITLE LIKE '%HVAC%')
ORDER BY TYPESVS;

REM Fire Protection System
SELECT * FROM WOS_EMER_URG
WHERE (WOTITLE LIKE '%FIRE%')
ORDER BY TYPESVS;

REM Plumbing System
SELECT * FROM WOS_EMER_URG
WHERE (WOTITLE LIKE '%WATER%')
ORDER BY TYPESVS;


spool off;
```

Appendix H. Queries Log File

```
SQL> SET HEADING ON
SQL> SET PAGESIZE 50000
SQL> SET NEWPAGE NONE
SQL> SET LINESIZE 300
SQL> SET FEEDBACK ON
SQL> SET COLSEP '|'
SQL>
SQL> REM Nuke view if it exists
SQL> DROP VIEW WOS_EMER_URG
  2
SQL> REM Create WOS_EMER_URG View
SQL> CREATE VIEW WOS_EMER_URG AS
  2  SELECT FACIDNR, WOTITLE, CREATEDATE, TYPESVS, WOIND
  3  FROM WORKORDERS
  4  WHERE (TYPESVS='E' OR TYPESVS='U' AND WOIND='J')
  5  ORDER BY TYPESVS;

View created.

SQL> REM SELECT * FROM WOS_EMER_URG;
SQL>
SQL> REM Electrical System
SQL> SELECT * FROM WOS_EMER_URG
  2  WHERE (WOTITLE LIKE '%POWER%' OR WOTITLE LIKE '%ELEC%')
  3  ORDER BY TYPESVS;
```

FACIDNR	WOTITLE	CREATEDATE	TYPESVS	WOIND
0	ELECTRIC PHASE OUT	141016	E	J
763	**NO POWER**	**140923**	**E**	**J**
81202	RADIONICS ALARM POWER OUTAGE	140929	E	J
81202	POWER OUT TO BLDGS	141203	E	J
22010	TROUBLESHOOT ELEC MOTOR	141204	E	J
13675	POWER OUTAGE/ RM 100	141212	E	J
81201	NO ELECT PWR ON PRISON GROUNDS	141212	E	J
81201	LOSS OF ELECT POWER TO BLDG	141212	E	J
10510	NO POWER TO FRYER & BOILER	141103	E	J
636	LOSS OF ELECTRICAL POWER	141110	E	J
636	NO POWER TO BLDG	141110	E	J
81202	POWER OUTAGE	141110	E	J
MULTI	ELECT VOLTAGE TO HIGH AT BLDGS	141113	E	J
6005	NO ELECT POWER TO BLDG	141113	E	J
81202	POWER OUTAGE	141117	E	J
81202	POWER SPIKE	141118	E	J
178	WELL PUMP INOP NO POWER	121210	E	J
81202	NO POWER	131226	E	J
7011	ASSIST FMS ON PATIAL POWER	131226	E	J
1335	ELECT POWER OUTAGE AT BLDG	131227	E	J
7011	**LOSS OF POWER**	**131230**	**E**	**J**
1768	BRUSH FIRE/POWER OUTAGE	131230	E	J
81202	POWER OUTAGE	140116	E	J
81201	ELECT POWER OUTAGE	140117	E	J
81202	REPAIR DOWN POWER LINE	131125	E	J
8401	ELECTRICAL BURNING SMELL	140124	E	J
8401	NO POWER	140124	E	J
81201	POWER OUTAGE	140124	E	J
81202	PROBABLE POWER OUTAGE	140129	E	J
81201	EMERG POWER OUTAGE	140130	E	J
MULTI	NO POWER	140203	E	J
8195	ELECT SWITCHING OPERATION	140220	E	J
81202	POWER OUTAGE	140224	E	J
81201	ELECT POWER OUTAGE	140224	E	J

81201	ELECT POWER OUTAGE ON N.BASE	140226	E	J
81202	POWER OUTAGE ON K7 FEEDER	140310	E	J
2526	AC POWER FAILURE	140210	E	J
81201	POWER OUTAGE	140210	E	J
81201	ELECTRIC POWER OUTAGE	140210	E	J
81202	POWER LINE DOWN BY FLAG POLE	140407	E	J
81201	K-5 ELECT POWER OUTAGE	140409	E	J
81202	ELECTRICAL POWER FAILURE	140411	E	J
81202	POWER OUTAGE	140416	E	J
759	PARTIAL POWER LOSS TO BLDG	140421	E	J
6510	**POWER OUTAGE**	**140423**	**E**	**J**
10510	ELECTRIC METER	140425	E	J
81202	NO POWER	140428	E	J
81202	NO POWER	140428	E	J
81202	POWER IS AT 195 VOLTS	140312	E	J
380	STRONG ELECTRICAL BURN SMELL	140313	E	J
81202	LOST POWER	140317	E	J
490	NO POWER TO THE BLDG	140317	E	J
221	POWER OUTAGE	140318	E	J
81201	ELECTRIC POWER OUTAGE	140326	E	J
81202	ELECTRICAL POWER LOSS	140331	E	J
81202	POWER GLITCH	140401	E	J
8195	LOSS ELEC PWR TO MISSILE TNGRS	140403	E	J
81202	NO POWER SLC-3 AREA	140507	E	J
13322	DORM HAS NO POWER	140602	E	J
81202	NO POWER	140602	E	J
11777	BURNING ELECTRICAL SMELL	140620	E	J
22310	INSTAL ELEC PWR FOR CLORINEPMP	140624	E	J
81202	POWER OUTAGE	140626	E	J
81202	POWER OUTAGE	140626	E	J
81201	NO POWER	140513	E	J
1740	POWER LINE UNSAFE	140513	E	J
12006	ELECTRICAL BURNING	140818	E	J
1555	AC POWER FAILURE	140819	E	J
81201	ELECT PWR LOSS-GLITCH AT BLDG	140714	E	J
81202	DOWN POWER LINE	140721	E	J
81202	POWER OUTAGE	140902	E	J
8173	CHECK ELECTRICAL EQUIPMENT	140908	E	J
81202	POWER OUTAGE	140930	E	J
81202	POWER OUTAGE	140930	E	J
81201	POWER OUTAGE	141006	E	J
81201	LOST POWER TO THE PRISON	141006	E	J
1950	POWER OUTAGE	141008	E	J
2	A/C DOWN&POWER OUTAGE	141014	E	J
81201	ELECTRIC LINE DOWN	141014	E	J
10577	PROVIDE ELECTRICAL POWER	130731	U	J
81201	REPLACE POWER POLE & ARM	130910	U	J
178	WELL PUMP INOP NO POWER	121210	U	J
81201	AIR DUCTING STRIP ON POWERLINE	131217	U	J
1335	TREE LAYING ACROSS ELEC WIRES	131223	U	J
13005	CHECK POWER TO THE BLDG	131226	U	J
7011	ASSIST FMS ON PATIAL POWER	131226	U	J
7011	LOSS OF POWER	131230	U	J
1768	BRUSH FIRE/POWER OUTAGE	131230	U	J
1967	ASSIST ON NO POWER UNDERGRND	140103	U	J
976	NO POWER AT ALL	140107	U	J
831	NO POWER TO BLDG	140109	U	J
81202	BASE WIDE POWER OUTAGE	140113	U	J
11777	ELECT CIRCUIT BREAKER INOP	140113	U	J
81202	POWER OUTAGE	140116	U	J
81201	ELECT POWER OUTAGE	140117	U	J
7425	REPAIR PUMP BOILER/NEED ELECT	131009	U	J
23225	TROUBLE SHOOT ELECTRICAL SYS	131021	U	J
1728	ELECT 240VOLT-3PHASE-100AMPS	131030	U	J
81201	POWER LINE HANGING DOWN/FUSE	131105	U	J

10525	PULL JACKS/SUPPORT ELECTRICIAN	131203	U	J
81202	POWER OUT	140124	U	J
1544	**EMERGENCY LIGHTS/ NO POWER**	**140127**	**U**	**J**
8401	INSTALL ELEC OUTLET FOR HVAC	140127	U	J
81202	PROBABLE POWER OUTAGE	140129	U	J
81201	EMERG POWER OUTAGE	140130	U	J
8290	TURN OFF ELECT POWER TO ROOM	140131	U	J
6601	EXPOSED ELECTRIC WIRES	140203	U	J
13122	REPAIR NO POWER TO AC UNIT	140203	U	J
857	GATE ELECT SOCKET INOP	140225	U	J
81202	2 POWER FLUCTUATIONS	140227	U	J
10713	ROOF DRAIN LEAK ONTO POWER BOX	140228	U	J
81202	TREE ON POWER LINE	140228	U	J
376	ELECTRIC POWER FAILING	140306	U	J
8425	TROUBLESHOOT OUTLET/ADD POWER	140205	U	J
8401	ELECT STRIKE LOCK DOOR REPAIR	140213	U	J
10713	ELECT ROLLUP DOOR WON'T OPEN	140218	U	J
1508	POWER TOO LOW IN BUILDING	140407	U	J
81202	POWER POLE LEANING	140408	U	J
81202	POWER POLE	140410	U	J
81202	POWER OUTAGE	140416	U	J
10343	NO ELECT PWR ALONG ONE WALL	140417	U	J
6601	ELECTRONIC COMBO NOT RESETTING	140417	U	J
976	PAC POWER OUTLETS TRBL MSG	140421	U	J
14016	RESTORE ELECTRICAL POWER	140423	U	J
1810	APPROX 5 ELECT OUTLETS INOP	140425	U	J
81202	NO POWER	140428	U	J
875	PARTIAL POWER LOSS AT BLDG	140428	U	J
13675	KILL-TURN OFF POWER TO PANEL	140430	U	J
10711	ELECT BREAKER KEEPS TRIPPING	140501	U	J
13222	DISCONNECT POWER TO FACILITY	140311	U	J
380	STRONG ELECTRICAL BURN SMELL	140313	U	J
10400	ELECTRIC WATER HEATER LEAK	140314	U	J
490	NO POWER TO THE BLDG	140317	U	J
1548	A/C POWER FAILURE	140317	U	J
10510	CHECK ELECTRICAL SHORT IN WALL	140320	U	J
81204	REPAIR ELECTRICAL LINE	140320	U	J
0	NO POWER TO BASE WASH RACK	140321	U	J
976	ELECTRICAL PROBLEM	140324	U	J
1559	COMMERCIAL POWER PROBLEMS	140324	U	J
81202	POWER LINE DOWN	140325	U	J
21200	T-MOBILE ELECTRICAL SUPPORT	140326	U	J
81201	T-MOBILE ELECTRICAL SUPPORT	140326	U	J
9505	POWER PULSING ON AND OFF	140331	U	J
1737	NO POWER IN RMS 16 & 18	140404	U	J
1704	ELECT POWER LOSS TO DIESEL STD	140506	U	J
81202	NO POWER SLC-3 AREA	140507	U	J
81201	ELECT PWR LOSS TO BLDGS	140507	U	J
11496	LOSS POWER TO GUARD SHACK	140512	U	J
16114	REPAIR BROKEN ELECT OUTLET	140605	U	J
7437	ELECTRICAL REPAIRS	140606	U	J
974	NO ELECT POWER TO TOWER 57	140612	U	J
0	POWER ON POLE ARCHING SWITCH	140613	U	J
1762	ELECT POWER LOSS	140616	U	J
11442	ELECTRICAL OUTLETS NOT WORKING	140617	U	J
12006	PULL ELECT JACKS TO KILL POWER	140619	U	J
976	ELECT POWER LOSS AT BLDG	140624	U	J
10400	ELECTRICAL PLUG DAMAGED	140625	U	J
81202	POWER OUTAGE	140626	U	J
81202	POWER OUTAGE	140626	U	J
11439	INSTAL 2 FOURPLUG ELEC OUTLETS	140626	U	J
81202	POWER OUT/TREES ON LINES	140512	U	J
857	ELECTRIC PANEL COVER	140515	U	J
16170	ELECTRICAL BOX CORROSION	140515	U	J
81201	ELECT POWER LOSS	140520	U	J

1846	RESTORE POWER	140520	U	J
857	HALF ELECT POWER LOSS S.GATE	140522	U	J
0	REPAIR ELECTRICAL CUTOUTS	140522	U	J
81201	REPAIR ELECTRIC ISSUE	140731	U	J
10400	REPAIR METAL PLATE ELEC BOX	140807	U	J
81201	LOSS ELECTRIC POWER	140807	U	J
8500	ELECTRIC OUTLET INOP	140808	U	J
302	REPAIR ELECRICAL POWER	140812	U	J
16170	ELECTRICAL OUTLET	140814	U	J
11248	RELOCATE ELECT LIGHT SWITCH	140626	U	J
0	NO POWER BREAKER TRIPPED	140627	U	J
9505	NO ELECTRICAL POWER	140701	U	J
8500	**LOST ELECTRICAL POWER**	**140703**	**U**	**J**
12006	DISCONNECT POWER	140710	U	J
12000	DISCONNECT POWER	140710	U	J
81201	ELECT PWR LOSS-GLITCH AT BLDG	140714	U	J
81202	POWER LINE/TREE POPPING SOUNDS	140715	U	J
6523	RESTORE POWER TO RM. 415	140723	U	J
81201	NOT GETTING ELECT PWR TO WELL	140723	U	J
11439	REPAIR A/C IN ELEC OFFICE	140724	U	J
10510	ELECT POWER LOSS TO DISPENSOR	140728	U	J
81201	POWER LOSS TO BUNKER	140728	U	J
81202	AC POWER FAILURE	140729	U	J
81202	POWER POLE INSULATOR DOWN	140729	U	J
11070	REINSTALL ELECT RECEPTACLE	140909	U	J
11451	DOORS ELECTRONICALLY OPEN	140916	U	J
8500	ELECT POWER LOSS IN ROOM	140929	U	J
81202	POWER OUTAGE	140930	U	J
5500	**NO POWER**	**141006**	**U**	**J**
23150	ELECT MOTOR INOP	141006	U	J
81201	POWER OUTAGE	141006	U	J
11070	BOILER OFF DUE TO POWER OUTAGE	141007	U	J
10510	NO ELECT PWR TO DRIVE THRU STA	141007	U	J
22405	REPAIR HOA ELECT SWITCH	141008	U	J
856	NEED WATER & FUEL/POWER PRO	141009	U	J
13330	INSTALL ELECTRL. OUTLET COVERS	141009	U	J
2	A/C DOWN&POWER OUTAGE	141014	U	J
1639	**NO POWER**	**141014**	**U**	**J**
11248	ELECTRIC WATER HEATER LEAKING	141015	U	J
9505	ELECT PWR CONTINUALLY GOES OUT	141021	U	J
8290	POWER OUT IN ROOM 239	140917	U	J
10728	POWER LINE LEANING	140923	U	J
81202	RADIONICS ALARM POWER OUTAGE	140929	U	J
81201	REPAIR ELECTRICAL OUTAGE	141124	U	J
11777	NOT GETTING ELEC PWR TO COMPTR	141124	U	J
935	ELECT POWER LOSS AT BLDG	141124	U	J
1968	NO ELECT POWER TO BLDG	141125	U	J
1682	ABOUT 1/2 POWER LOSS AT BLDG	141202	U	J
1682	HALF POWER TO THE BLDG	141202	U	J
81202	POWER OUT TO BLDGS	141203	U	J
1544	NO POWER & ELECT BURNING SMELL	141203	U	J
81201	ELECTRIC POWER LINE DOWN	141203	U	J
11439	ELECTRONIC KEY	141204	U	J
8500	SEVERAL VAV'S NOT POWERED	141204	U	J
11070	PARTIAL POWER OUTTAGE	141209	U	J
81202	POWER OUTTAGE	141210	U	J
11025	ELECTRICAL OUTLETS NOT WORKING	141211	U	J
81202	POWER OUTTAGE	141211	U	J
6510	POWER OUTAGE	141212	U	J
81201	ELECT POWER LINE CAME DOWN	141212	U	J
81202	POWER OUTTAGE	141212	U	J
6601	WATER LEAK/ INTO ELECTRICAL	141212	U	J
81201	POWER LINE WIRES HANGING DOWN	141215	U	J
5010	FIX ELECTRICAL BOX AT SITE 12	141029	U	J
81201	SCHEDULED WORK/ELECTRICAL SUP.	141031	U	J

21308	RESECURE POLE ELECT BOX LOOSE	141105	U	J
1501	PULL/KILL POWER	141106	U	J
636	LOSS OF ELECTRICAL POWER	141110	U	J
636	NO POWER TO BLDG	141110	U	J
MULTI	ELECT VOLTAGE TO HIGH AT BLDGS	141113	U	J
636	NO POWER	141114	U	J
525	**POWER LOSS**	**141114**	**U**	**J**
661	ELECT POWER LOSS AT BLDG	141118	U	J
8290	3 OUTLETS HAVE NO POWER	141118	U	J
11439	ELECT SHOCK FROM BEAD BLASTER	141119	U	J
81201	ELECTRICAL DROPPED PHASE	141119	U	J

241 rows selected.

```
SQL> REM HVAC System
SQL> SELECT * FROM WOS_EMER_URG
  2  WHERE (WOTITLE LIKE '%A/C%' OR WOTITLE LIKE '%HVAC%')
  3  ORDER BY TYPESVS;
```

FACIDNR	WOTITLE	CREATEDATE	TYPESVS	WOIND
1508	RESET HVAC SYSTEMS	140623	E	J
8339	CHECK/REPAIR INOP. A/C UNIT	140624	E	J
10577	A/C UNIT TURNED OFF	140625	E	J
7025	**HVAC IS DOWN**	**140818**	**E**	**J**
7015	**A/C UNIT STOPPED WORKING**	**140825**	**E**	**J**
8195	**HVAC UNIT DOWN**	**141110**	**E**	**J**
7025	HVAC ALARM	140702	E	J
2	A/C DOWN&POWER OUTAGE	141014	E	J
0	A/C ECONOMIZER TO VENT OUT	141126	E	J
8195	HVAC UNIT DOWN	141110	E	J
7015	A/C STOPPED WORKING	140825	E	J
10400	A/C LEAKING WATER FROM CEILING	130520	U	J
13120	HVAC UNIT MAKING LOUD NOISE	130605	U	J
11439	HVAC UNIT LEAKS WATER	130701	U	J
8290	A/C NOT BLOWING COLD AIR	130710	U	J
326	A/C BLOWING HOT AIR	130724	U	J
11439	REPAIR PORTABLE A/C	130822	U	J
1937	HVAC UNIT NEEDS REPAIR/ADJUST	130919	U	J
10130	**HVAC NOT WORKING**	**130925**	**U**	**J**
8314	HVAC PROBLEM TOO HOT/TOO COLD	131216	U	J
10525	A/C UNIT FLOODING ROOM	131021	U	J
12000	HVAC UNIT MAKING LOUD NOISE	131025	U	J
976	HVAC UNIT PRESSURE SUPPLY	131213	U	J
8401	INSTALL ELEC OUTLET FOR HVAC	140127	U	J
10577	HVAC CRACK UNITS #1 & #2 INOP	140129	U	J
0	HVAC A/C UNIT #1 INOP	140130	U	J
1	A/C ECONOMIZER VENT INOP	140220	U	J
8195	HVAC CRACK UNIT INOP	140220	U	J
836	3 HVAC CHILLERS INOP	140228	U	J
6525	HVAC NOT WORKING	140228	U	J
1508	COOLING FAN FOR A/C COIL INOP	140303	U	J
326	HVAC UNITS INOP	140305	U	J
10660	**HVAC NOT WORKING**	**140206**	**U**	**J**
1	A/C IS DOWN	140211	U	J
8314	HVAC UNIT LEAKING	140218	U	J
8195	A/C INOP, SERVER RM TOO HOT	140408	U	J
10400	HVAC UNIT MAKING NOISE ON ROOF	140429	U	J
7011	**A/C NOT WORKING**	**140312**	**U**	**J**
1544	HVAC INOPERABLE	140314	U	J
1548	A/C POWER FAILURE	140317	U	J
1507	HVAC CRACK UNIT TEMP CHANGE	140324	U	J
1546	LEAKING HVAC UNIT	140507	U	J
8500	A/C NOT BLOWING COLD AIR	140512	U	J
8500	HVAC CRACK UNIT NOT BLOWINGAIR	140604	U	J
10400	A/C REPAIR TOO HOT	140605	U	J

12006	REPAIR LEAKING A/C UNIT	140606	U	J
11013	HVAC/BOILER EVAL	140617	U	J
11777	INSTALL PORTABLE A/C UNITS	140620	U	J
1508	RESET HVAC SYSTEMS	140623	U	J
1937	BIG PORTABLE HVAC UNIT LEAKS	140623	U	J
6670	HVAC UNITS CHECKOUT AT BLDG	140626	U	J
1762	RESET A/C ALARM	140807	U	J
9192	A/C UNIT LEAKS WATER ON DESK	140818	U	J
5500	A/C LEAKING WATER	140825	U	J
1546	HVAC NOISE	140825	U	J
6525	REPAIR LOUD/BLOWING STRONG A/C	140707	U	J
6525	STRONG VIBRATION SOUNDS - HVAC	140722	U	J
11439	REPAIR A/C IN ELEC OFFICE	140724	U	J
12000	**REPAIR INOP. HVAC**	**140728**	**U**	**J**
8195	NO A/C	140902	U	J
7420	A/C SQUEEKING IND LIGHT ON	140908	U	J
8500	HVAC UNITS NON OPERABLE	140908	U	J
13640	HVAC UNIT OPERATING TEMP CHECK	140908	U	J
6601	HVAC PROBLEMS-TOO HOT	140908	U	J
13750	CHECK-INSPECT HVAC SYSTEM	140912	U	J
2	A/C DOWN&POWER OUTAGE	141014	U	J
8500	**REPAIR A/C UNITS INOP**	**140916**	**U**	**J**
8173	CHECK HVAC TEMP	140916	U	J
6670	REPAIR HVAC/LAB IS TOO HOT	140926	U	J
1743	HVAC SYSTEM LEAKING WATER	140926	U	J
8195	HVAC CHECK - TOO HOT	141202	U	J
1638	2 HVAC CRACK UNITS RESET-REPAR	141215	U	J
13123	REPAIR HVAC FANS/PIPES	141024	U	J
8290	SERVER ROOM A/C INOP-LEFT UNIT	141024	U	J
16200	LOUD NOISE FROM HVAC SYSTEM	141030	U	J
2000	A/C INOP	141106	U	J
1610	HVAC SHOWING ALARM/DIAGNOSTICS	141107	U	J
8195	HVAC UNIT DOWN	141110	U	J
1652	REPAIR HVAC UNIT	141121	U	J

79 rows selected.

```
SQL> REM Fire Protection System
SQL> SELECT * FROM WOS_EMER_URG
  2  WHERE (WOTITLE LIKE '%FIRE%')
  3  ORDER BY TYPESVS;
```

FACIDNR	WOTITLE	CREATEDATE	TYPESVS	WOIND
13851	REAL WORLD...911 FIRE RESPONSE	130918	E	J
177	FIRE ALARM ACTIVATION	131226	E	J
1768	BRUSH FIRE/POWER OUTAGE	131230	E	J
84302	FIRE HYDRANT	140121	E	J
1555	FIRE ALARM PANEL	131105	E	J
977	REPAIR FIRE SYSTEM	131206	E	J
MULTI	FIRE ALARM ACTIVATION	140127	E	J
852	FIRE ALARM ACTIVATION	140303	E	J
8425	FIRE ALARM	140303	E	J
1555	FIRE ALARM PANEL	140428	E	J
0	FIRE RESPONSE	140430	E	J
MULTI	FIRE ALARM WILL NOT RESET	140623	E	J
0	FIRE DOZER SUPPORT	140513	E	J
13001	FIRE ALARM PANEL	140804	E	J
490	FIRE ALARM SYSTEM	140807	E	J
490	FIRE ALARM PANEL	140811	E	J
7025	FIRE ALARM PANEL	140811	E	J
1610	FIRE ALARM PANEL	140815	E	J
10577	**FIRE ALARM PANEL**	**140821**	**E**	**J**
23229	FIRE CODES	140827	E	J
974	FIRE PANEL	140902	E	J
1810	FIRE PANEL HASS TROUBLE	140902	E	J

1335	FIRE ALARM PANEL	140902	E	J
8314	AUTOMATIC FIRE CODES	140902	E	J
13862	FIRE ALARM INOP	141020	E	J
0	FIRE ALARM PANEL COMM FAILURE	141020	E	J
0	REPORT OF FIRE	140922	E	J
10510	CANNOT RESET FIRE PANEL	141208	E	J
9005	FIRE ALARM PANEL BEEPING	141117	U	J
6816	FIRE ALARM BEEPING	141118	U	J
7025	FIRE ALARM PANEL TROUBLE	141119	U	J
1800	REPAIR FIRE PULL STATION	141121	U	J
13851	REAL WORLD...911 FIRE RESPONSE	130918	U	J
23240	REPAIR FIRE SPRINKLER PIPES	130925	U	J
14400	REPLACE FIRE SUPRS FLOW SWITCH	131213	U	J
23209	FIRE PUMP ACTIVATION	131223	U	J
177	FIRE ALARM ACTIVATION	131226	U	J
1768	BRUSH FIRE/POWER OUTAGE	131230	U	J
1746	FIRE ALARM PANEL BUZZING	140113	U	J
0	BASE FIRE SUPPORT	140113	U	J
8425	FIRE ALARM PANEL	140114	U	J
16170	FIRE DOOR HINGE BROKEN	140117	U	J
84302	FIRE HYDRANT	140121	U	J
1555	FIRE ALARM PANEL	131105	U	J
1800	FIRE ALARM PANEL	131121	U	J
6670	FIRE ALARM PANEL BEEPING	131206	U	J
977	REPAIR FIRE SYSTEM	131206	U	J
341	FIRE ALARM BATTERY	131213	U	J
MULTI	FIRE ALARM ACTIVATION	140127	U	J
8175	FIRE DOOR WON'T STAY OPEN	140129	U	J
9005	RESET FIRE ALARM	140227	U	J
2007	FIRE ALARM PANEL	140228	U	J
84302	FIRE HYDRONT BUSTED LEAKS ALOT	140213	U	J
13123	FIRE ALARM SYSTEM NOT WORKING	140409	U	J
84302	FIRE HYDRANT INOP	140410	U	J
1555	FIRE ALARM PANEL	140428	U	J
6670	FIRE SPRINKLER SYS LEAKING	140428	U	J
6670	FIRE ALARM PANEL	140429	U	J
1743	FIRE ALARM PANEL	140319	U	J
13007	FIRE PANEL IS BUZZING	140331	U	J
8401	FIRE PANEL	140616	U	J
8415	FIRE SYS RIZER REPAIR	140618	U	J
MULTI	FIRE ALARM WILL NOT RESET	140623	U	J
14400	FIRE ALARM PANEL	140527	U	J
1670	FIRE SUPPRESSION LINE LEAKING	140801	U	J
13330	FIRE ALARM SYSTEM BEEPING	140801	U	J
6817	FIRE SUPPRESSION SYSTEM	140806	U	J
84302	FIRE HYDRANT LEAKING	140811	U	J
10577	FIRE ALARM PANEL	140821	U	J
84302	REPAIR FIRE HYDRONT	140821	U	J
1800	FIRE ALARM PANEL-BEEPING	140825	U	J
23229	FIRE CODES	140827	U	J
MULTI	LOW WATER PRESSURE TO FIRESPRK	140701	U	J
7025	FIRE PANEL IN TROUBLE	140702	U	J
84302	WATER LEAK BY EXT.FIRE HYDRONT	140722	U	J
1	REPAIR FIRE HYDRANT	140728	U	J
1810	FIRE PANEL HASS TROUBLE	140902	U	J
7025	FIRE ALARM PANEL CHECK	140908	U	J
11013	ISOLATE FIRE ALARM SYSTEM	140910	U	J
6525	FIRE ALARM IN TROUBLE/BEEPING	141008	U	J
1705	FIRE ALARM TROUBLE	141014	U	J
8500	FIRE ALARM PANEL BEEPING	141020	U	J
13675	FIRE DOOR LATCH BROKEN	140916	U	J
16200	**FIRE ALARM PANEL**	**141201**	**U**	**J**
9005	FIRE ALARM NEEDS TO BE RESET	141205	U	J
10510	CANNOT RESET FIRE PANEL	141208	U	J
6523	FIRE ALARM BEEPING	141209	U	J

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13001     |FIRE ALARM PANEL                    |141209    |U      |J
6525      |RESET FIRE ALARM                    |141212    |U      |J
9190      |INSPECT/ FIRE ALARM PANEL           |141212    |U      |J
13135     |FIRE ALARM BEEPING                  |141218    |U      |J
13123     |FIRE ALARMS BEEPING                 |141218    |U      |J
84302     |FIRE HYDRANT LEAKING                |141023    |U      |J
1896      |REPAIR FIRE ALARM                   |141029    |U      |J
8314      |FIRE ALARM GOING OFF                |141110    |U      |J
8314      |FIRE ALARM PANEL GOING OFF          |141112    |U      |J

97 rows selected.

SQL> REM Plumbing System
SQL> SELECT * FROM WOS_EMER_URG
  2  WHERE (WOTITLE LIKE '%WATER%')
  3  ORDER BY TYPESVS;
FACIDNR   |WOTITLE                             |CREATEDATE|TYPESVS|WOIND
----------|------------------------------------|----------|-------|-------
13330     |NO HOT WATER                        |140825    |E      |J
13330     |NO HOT WATER                        |140825    |E      |J
11041     |2 1/2 IN. WATER LINE                |140825    |E      |J
13330     |NO HOT WATER                        |140826    |E      |J
84201     |1 INCH WATER LINE BREAK             |140827    |E      |J
10144     |WATER TEMP DROPPING                 |140707    |E      |J
9192      |WATER LEAKING                       |140714    |E      |J
84200     |WATER SPILLING ON TO NEVADA         |140714    |E      |J
13851     |WATER LEAKING FROM CEILING          |140716    |E      |J
13120     |NO HOT WATER TO DORM                |140718    |E      |J
84201     |WATER GUSHING FROM GROUND           |140724    |E      |J
13857     |NO HOT WATER                        |140728    |E      |J
13863     |NO HOT WATER TO ROOMS               |140902    |E      |J
13863     |WATER LEAKING IN ROOM               |140902    |E      |J
13852     |WATER LEAK IN CEILING               |140902    |E      |J
10400     |NO COLD WATER                       |140908    |E      |J
13330     |BROWN WATER COMING OUT FAUCETS      |140908    |E      |J
13330     |NO HOT WATER                        |140910    |E      |J
8415      |WATER FROM ROOF/ WATER BREAK        |141014    |E      |J
1622      |WATER LEAK FROM UNDERGROUND         |141015    |E      |J
23225     |BAD WATER LINE LEAK                 |140922    |E      |J
23209     |WATER HOSE RUNNING                  |140923    |E      |J
9320      |WATER LEAK                          |140923    |E      |J
12000     |WATER LEAK                          |140925    |E      |J
13864     |NO HOT WATER TO THE ROOM            |141201    |E      |J
13864     |NO HOT WATER                        |141201    |E      |J
84201     |WATER LEAKING FROM PIPE             |141208    |E      |J
1521      |BROKEN WATER PUMP                   |141212    |E      |J
1559      |REPAIR WATER LEAKS                  |141215    |E      |J
1740      |WATER LEAK                          |141024    |E      |J
84201     |POSSIBLE WATER BREAK                |141027    |E      |J
84101     |REPLACE WATER LINE 18" VALVE        |141029    |E      |J
84101     |WATER MAIN BREAK                    |141030    |E      |J
10130     |NO HOT WATER                        |141103    |E      |J
10130     |NO HOT WATER TO GYM                 |141105    |E      |J
13860     |BOILER LEAKING WATER                |141107    |E      |J
10130     |NO HOT WATER                        |141110    |E      |J
5010      |WATER LINE BREAK                    |141112    |E      |J
13330     |NO HOT WATER                        |141112    |E      |J
84101     |WATER BREAK                         |141120    |E      |J
10400     |WATER LEAK IN CEILING               |130412    |E      |J
375       |LOW WATER PRESSURE                  |130425    |E      |J
10314     |NO GAS IN BLDG FOR HOT WATER        |130627    |E      |J
13859     |NO HOT WATER                        |130916    |E      |J
84202     |POLE FELL ON WATER LINE             |130124    |E      |J
13857     |WATER LEAKING INTO ROOM             |130211    |E      |J
11041     |NO HOT WATER FOR THE TUB            |131220    |E      |J
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21298	NO WATER PRESSURE	131226	E	J
10660	WATER BREAK	131231	E	J
1335	POSSIBLE WATER BREAK	140102	E	J
6525	BROKEN WATER LINE	140113	E	J
13330	NO HOT WATER	140113	E	J
16170	WATER LEAK	140113	E	J
9192	NO HOT WATER IN BLDG	140115	E	J
13330	NO HOT WATER	140116	E	J
13330	NO HOT WATER	140121	E	J
1521	WATER LINE BROKEN	131206	E	J
1521	WATER LINE BROKEN	131206	E	J
13330	NO HOT WATER	140127	E	J
12901	WATER GOING INTO ROOM AT FLOOR	140128	E	J
13330	NO HOT WATER	140131	E	J
13330	NO WATER IN FACILITY	140220	E	J
11070	NO HOT WATER	140224	E	J
10343	WATER LEAKING	140224	E	J
10726	WATER WARNING ALARM	140303	E	J
84201	POSSIBLE WATER BREAK	140305	E	J
13330	NO HOT WATER	140210	E	J
13330	NO HOT WATER	140210	E	J
13330	NO HOT WATER	140218	E	J
13863	NO HOT WATER	140407	E	J
13853	WATER DRIPPING FROM CEILING	140407	E	J
0	BROKEN WATER VALVE	140416	E	J
11070	NO HOT WATER	140417	E	J
16177	HOT WATER FAUCET WONT TURN OFF	140423	E	J
11439	HOT WATER FAUCET	140424	E	J
21308	BOILER RM PIPE/RUNNING WATER	140424	E	J
13330	NO HOT WATER	140313	E	J
13007	NO HOT WATER	140314	E	J
32007	WATER GUSHING FROM MANHOLE	140317	E	J
13330	NO HOT WATER	140318	E	J
13330	NO HOT WATER	140319	E	J
13330	NO HOT WATER	140321	E	J
688	WATER PUMP INOP-TRIPPED BREAKR	140328	E	J
13330	NO HOT WATER	140401	E	J
6525	WATER FLOODING BUILDING	140403	E	J
13330	NO HOT WATER	140506	E	J
13858	WATER LEAK COMING FROM CEILING	140509	E	J
10510	YELLOW DIRTY WATER	140605	E	J
MULTI	NO WATER PRESSURE	140605	E	J
32008	WATER BREAK	140611	E	J
13730	CEILING WATER LEAKS	140611	E	J
13730	CEILING WATER LEAKS	140611	E	J
84200	GREEN BOX LEAKING WATER	140618	E	J
0	WATER BREAK IN THE GROUND	140513	E	J
13330	WATER LEAKING FROM CEILING	140519	E	J
13122	WATER BACKED UP 7 LEAKING	140527	E	J
11042	WATER BACKING UP IN ROOMS	140527	E	J
84201	WATER IS GUSHING BACK OF BLDG	140527	E	J
10577	WATER LEAKING FROM CEILING	140805	E	J
84101	WATER BREAK	140805	E	J
84101	WATER BREAK	140805	E	J
10400	BROWN WATER	140811	E	J
84200	WATER BUBBLING UP	140821	E	J
10400	WATER LEAK IN CEILING	130412	U	J
375	LOW WATER PRESSURE	130425	U	J
10400	A/C LEAKING WATER FROM CEILING	130520	U	J
13853	WATER LEAKING FROM CEILINGCORE	130626	U	J
10314	NO HOT WATER/PILOT LIGHT OUT	130627	U	J
11439	HVAC UNIT LEAKS WATER	130701	U	J
84101	WATER LINE LEAK	130708	U	J
175	NO WATER GOING INTO BLDG	130729	U	J
13854	NO HEAT/HOT WATER	130801	U	J

10130	WATER LEAKS IN MECH ROOM	130814	U	J
9360	WATER LEAKS IN RM/STANDING WTR	130903	U	J
10130	ICE MACHINE LEAKING WATER	130903	U	J
13859	NO HOT WATER	130916	U	J
10366	WATER LEAKING FROM THE CEILING	130916	U	J
1987	WATER NOT FILLING IN EXTERTANK	130917	U	J
1559	REPLACE 40 GAL SIZE WATER HTR	130919	U	J
13854	WATER HEATER/LIMIT SWITCH	130920	U	J
84101	EXT.WATER VALVE OFF MAIN LEAKS	120730	U	J
21206	REPAIR LEAKING WATER TANK	120917	U	J
84202	WATER LEAKING BY BACKFLOW PVTR	121107	U	J
13856	NO HEAT/HOT WATER	121128	U	J
181	NO WATER PRESSURE	130107	U	J
84202	POLE FELL ON WATER LINE	130124	U	J
13857	WATER LEAKING INTO ROOM	130211	U	J
16200	WATER LEAK IN KITCHEN	131216	U	J
13852	WATER LEAKS FROM CEILING IN RM	131217	U	J
84101	WATER LINE PIPE BUSTED LEAKING	131218	U	J
10577	ALL SINKS SPRAYING OUT WATER	131219	U	J
13330	NO HOT WATER	131219	U	J
13852	WATER COMES DOWN FROM 2RM WALL	131219	U	J
799	WATER LEAKING FROM CEILING	131220	U	J
11041	NO HOT WATER FOR THE TUB	131220	U	J
1657	WATER LEAK IN THE WALL	131226	U	J
21290	NO WATER GOINGTO HORSE STABLES	131226	U	J
84201	WATER BREAK	131230	U	J
811	WATER RUNNING	131230	U	J
1737	TOILET LEAKING WATER ON FLOOR	140103	U	J
8314	WATER LEAKING INTO ROOM	140106	U	J
13330	NO WATER PRESSURE TO SINK	140107	U	J
1743	BROKEN WATER LINE	140107	U	J
7425	GAS WATER HEATER	140109	U	J
9005	TOILET EMERGING WATER	140110	U	J
6525	BROKEN WATER LINE	140113	U	J
13330	NO HOT WATER	140113	U	J
16170	WATER LEAK	140113	U	J
50201	WATER LEAK	140114	U	J
50201	WATER LEAK	140114	U	J
84101	BROKEN WATER LINE	140114	U	J
13330	NO HOT WATER	140114	U	J
10601	CHECK PIPE SPRAYING WATER OUT	140117	U	J
660	**NO WATER IN FACILITY**	**131009**	**U**	**J**
764	HIGH WATER PRESSURE	131010	U	J
13854	NO HOT WATER/TEMP TO LOW	131010	U	J
1749	HOT WATER HEATER LEAKING	131010	U	J
13862	NO HEAT & HOT WATER IN BLDG	131023	U	J
9360	HOT WATER HEATER LEAKING	131025	U	J
11042	HOT WATER HEATER INOP	131028	U	J
7015	HOT WATER LINE LEAKING	131029	U	J
13330	WATER LEAKS UNDER HOOD AT LITE	131029	U	J
16156	WATER FOUNTAIN LEAKING	131114	U	J
13120	SHOWER HAS NO HOT WATER	131115	U	J
9192	NO HOT WATER COMING IN SHOWER	131203	U	J
871	HOT WATER HEATER LEAKING	131205	U	J
84101	WATER LEAKING ALOT FROM PIPING	131206	U	J
84101	WATER LEAKING ALOT FROM PIPING	131206	U	J
1521	WATER LINE BROKEN	131206	U	J
1521	WATER LINE BROKEN	131206	U	J
12006	WATER INSIDE COMM VAULT	131209	U	J
0	WATER TANK OVERFLOWING	131209	U	J
9307	WATER HEATER LEAKING	131209	U	J
13854	WATER LEAKING ALOT INTO 2 RMS	131211	U	J
9192	NO HOT WATER TO SHOWER	131212	U	J
872	WATER PIPE SUPPLY LINE BROKEN	131212	U	J
13848	WATER BREAK	140121	U	J

525	WATER REGULATOR	140123	U	J
13330	WATER COMING OUT FROM BOILERRM	140123	U	J
7015	WATER LEAKS AT CEILING IN ROOM	140127	U	J
84201	REPAIR BROKEN WATER LINE	140129	U	J
10130	WATER LEAKS HOLE CEILING DUCT	140130	U	J
84101	BROKEN WATER PIPE	140203	U	J
7525	NO HOT WATER	140204	U	J
13330	**NO WATER IN FACILITY**	**140220**	**U**	**J**
11070	NO HOT WATER	140221	U	J
10343	WATER LEAKING	140224	U	J
6670	LEAKING WATER HEATER	140224	U	J
84200	WATER LEAK	140224	U	J
9320	WATER FAUCETS WATER COLORED	140224	U	J
6523	WATER LEAK INTO BUILDING	140226	U	J
83202	SEWER TYPE WATER LEAKING ALOT	140226	U	J
809	WATER LEAKED ON FLOOR	140227	U	J
13135	WATER FLOODING THRU WALL IN RM	140228	U	J
10728	WATER LEAKS IN BUILDING	140228	U	J
84201	WATER LINE BREAK	140228	U	J
7015	WATER FLOODS WALKWY/2ND FLOOR	140228	U	J
1840	REMOVE WATER FROM ROOM IN BLDG	140228	U	J
12000	WATER LEAKING THRU WINDOWS	140228	U	J
13320	WATER LEAKING INTO ROOM/CLOSET	140228	U	J
10726	WATER WARNING ALARM	140303	U	J
84201	8 INCH WATER LINE	140303	U	J
9192	TOILET TANK LEAKING WATER	140304	U	J
10525	FAUCET HANDLE BROKE-WATER LEAK	140305	U	J
13862	NOT GETTING HOT WATER/HEATING	140306	U	J
9190	WATER DRIPS FROM CEILING BYFAN	140307	U	J
11070	NO HOT WATER	140310	U	J
13330	NO HOT WATER	140205	U	J
84101	14" WATER LINE HIT	140206	U	J
84101	NO WATER TO BLDGS	140206	U	J
10314	NO WATER GOING TO BLDG	140206	U	J
9192	WATER LEAKING AT CEILING	140206	U	J
13330	SOME WATER LEAKS INSIDE OF BDG	140206	U	J
8195	WATER LEAKING INTO ROOM	140206	U	J
10343	WATER DRIPPING ON 60" MONITOR	140206	U	J
6601	WATER DRIPING DOWN ON LITE FIX	140206	U	J
11439	WATER LEAKING UPSTAIRS DRAIN	140206	U	J
23215	WATER LEAKING INTO 2 ROOMS	140206	U	J
84101	WATER LINE BREAK	140207	U	J
9192	WATER LEAKING FROM SHOWER HNDL	140207	U	J
6670	BIG HOT WATER HEATER LEAKING	140211	U	J
13865	LOW WATER PRESSURE	140211	U	J
13330	WATER SOFTENER	140212	U	J
13330	NOT HOT WATER	140212	U	J
12000	NO WATER FLOW TO WTR COOLER	140212	U	J
84201	REPAIR PARKING LOT WATER LEAK	140213	U	J
13330	NO HOT WATER	140218	U	J
10728	PIPING LEAKING WATER NEAR DOOR	140218	U	J
13853	WATER DRIPPING FROM CEILING	140407	U	J
13853	WATER DRIPPING FROM CEILING	140407	U	J
12006	CEILING LEAK HOT WATER RETURN	140408	U	J
8173	WATER LEAK	140410	U	J
11070	HOT WATER TEMP TO COLD	140410	U	J
11041	TOILET LEAKS WATER AT WALL	140411	U	J
13330	NO HOT WATER	140414	U	J
13330	HOT WATER FAUCET SPRAYSOUT-RUN	140414	U	J
84101	WATER BREAK	140415	U	J
84101	CONTRACTOR BROKE 1" WATER LINE	140416	U	J
0	BROKEN WATER VALVE	140416	U	J
13750	SMALL WATER HEATER LEAKING	140417	U	J
13750	SMALL WATER HEATER LEAKING	140417	U	J
11070	NO HOT WATER	140417	U	J

12006	WATER LINE LEAK	140421	U	J
11070	NO HOT WATER	140423	U	J
16177	HOT WATER FAUCET WONT TURN OFF	140423	U	J
16177	HOT WATER FAUCET WONT TURN OFF	140423	U	J
11439	HOT WATER FAUCET	140424	U	J
16170	FAUCETS WATER COMING OUT BROWN	140428	U	J
84201	POSSIBLE WATER BREAK	140428	U	J
11041	**NO WATER TO HALF OF BLDG RIGHT**	**140428**	**U**	**J**
13853	WATER LEAKING OVER RMS 298/297	140429	U	J
8290	WATER FAUCET KEEPS RUNNING	140430	U	J
84201	POSSIBLE WATER BREAK	140310	U	J
84201	WATER LINE HIT-DAMAGE REPAIR	140311	U	J
84201	WATER BREAK	140311	U	J
13330	NO HOT WATER	140311	U	J
1559	WATER DRIPPING AT RECEPTICALS	140312	U	J
10144	LEAKING WATER SPICKET	140312	U	J
10400	ELECTRIC WATER HEATER LEAK	140314	U	J
13330	NO HOT WATER	140317	U	J
84101	WATER WAS TURNED OFF	140317	U	J
84201	WATER BREAK	140318	U	J
11510	WATER LEAKING ON FLOOR	140318	U	J
11248	BROWN COLOR WATER RUNS IN SINK	140318	U	J
11070	REPAIR NO HOT WATER TO BLDG.	140318	U	J
13121	WATER TAKES 30 MINS TO HEAT	140318	U	J
1338	NO HOT WATER	140319	U	J
10366	WATER LEAK	140319	U	J
1840	WATER UNDER RAISED FLOOR	140321	U	J
10400	WATER LEAKS DOWN FROM WALL	140324	U	J
10525	WATER LEAKING INTO ROOM	140326	U	J
MULTI	NO HOT WATER	140326	U	J
6525	WATER FLOODING BUILDING	140403	U	J
13330	NO HOT WATER	140506	U	J
0	URINAL LEAKING WATER	140506	U	J
13858	WATER LEAK COMING FROM CEILING	140509	U	J
13120	NO HOT WATER	140509	U	J
12006	MULTIPLE WATER LEAKS INTO BLDG	140530	U	J
875	REPAIR WATER CIRC. PUMP	140604	U	J
875	REPAIR WATER CIRC. PUMP	140604	U	J
84101	WATER FLOODING IN FRONT OF BDG	140604	U	J
10510	SINK WATER SPRAYER LEAKING	140604	U	J
84201	BROWN WATER DETECTED	140605	U	J
MULTI	NO WATER PRESSURE	140605	U	J
84101	WATER BREAK FRONT OF BDG 16177	140606	U	J
10400	WATER LEAKING DOWN WALL	140610	U	J
13853	WATER DRIPS AT HEATER CORE PNL	140610	U	J
13730	CEILING WATER LEAKS	140611	U	J
13848	WATER LEAK FROM CEILING	140611	U	J
8195	BROWN WATER COMING OUT	140611	U	J
13858	HEATING CORE WATER LEAK	140616	U	J
9190	4 FLOOR DRAINS WATER BACKS UP	140617	U	J
84200	GREEN BOX LEAKING WATER	140618	U	J
21308	WATER PIPE BREAK NEAR BLDG	140619	U	J
84101	WATER LEAKING AT SAMPLING STA	140623	U	J
10711	SHOWER WATER WON'T SHUT OFF	140624	U	J
9192	NO HOT WATER FROM SHOWER	140625	U	J
13330	HOT WATER PIPE SPRAYS ON FLOOR	140625	U	J
2500	ALL WATER COMINGOUT RUST COLOR	140625	U	J
10130	WATER WON'T TURN OFF COMPLETLY	140625	U	J
21298	WATER PRESSURE TO LOW FOR USE	140625	U	J
13675	TOILET WATER LEAKING ON FLOOR	140626	U	J
13330	NO HOT WATER	140512	U	J
1546	WATER LEAKING IN BOILER ROOM	140512	U	J
82401	WATER BREAK	140513	U	J
1521	WATERLINE BREAK	140513	U	J
13406	WATER LEAK MECH ROOM	140514	U	J

9190	NO HOT WATER	140515	U	J
6601	WATER LEAKING INTO ROOM #170	140516	U	J
12000	WATER LEAK	140519	U	J
11477	SHOWER HAS NO WATER PRESSURE	140520	U	J
10130	WATER LEAKING THROUGH CEILING	140520	U	J
10400	HOT WATER FAUCET	140520	U	J
13675	WATER LEAKING ALOT INTO RM 121	140521	U	J
13122	WATER BACKED UP 7 LEAKING	140527	U	J
84201	WATER IS GUSHING BACK OF BLDG	140527	U	J
11070	DISCOLORED WATER IN BUILDING	140527	U	J
10144	NO HOT WATER FOR SHOWERS	140527	U	J
12006	WATER COMING OUT OF ROOM	140529	U	J
9190	WATER BACKING UP DISH RM DRAIN	140529	U	J
9192	TOILET LEAKING WATER AT BOTTOM	140529	U	J
1615	REPAIR WATER LINE LEAK	140801	U	J
10577	WATER LEAKING FROM CEILING	140805	U	J
84101	WATER BREAK	140805	U	J
84101	WATER BREAK	140805	U	J
16200	**NO WATER/TOILETS NOT FLUSHING**	**140806**	**U**	**J**
11146	REPL WATER CLOSET HANDLES	140806	U	J
8175	CONSTANT RUNNING WATER SOUND	140808	U	J
10400	BROWN WATER	140811	U	J
490	REPAIR WATER HEATER	140811	U	J
13330	NO HOT WATER	140812	U	J
9192	WATER RUNS IN TOILETS-FLOODS	140813	U	J
16170	WATER FOUNTAIN	140814	U	J
9192	A/C UNIT LEAKS WATER ON DESK	140818	U	J
6523	WATER COMING OUT VALVE STAY ON	140819	U	J
1974	NO WATER TO TOILET	140820	U	J
13750	REPAIR WATER BREAK	140820	U	J
10577	WATER DRIPPING THROUGH FIXTURE	140820	U	J
84200	WATER BUBBLING UP	140821	U	J
84201	WATER BREAK	140821	U	J
10375	WATER COMING UP IN BOTH RESTRM	140821	U	J
11070	NO HOT WATER	140822	U	J
13330	WATER LEAKING LIGHT FIXTURES	140825	U	J
5500	A/C LEAKING WATER	140825	U	J
10577	WATER LEAK	140827	U	J
5010	BROWN WATER	140627	U	J
9192	NO HOT WATER FROM SHOWER	140701	U	J
MULTI	LOW WATER PRESSURE TO FIRESPRK	140701	U	J
7025	WATER LEAKING INTO HALLWAY	140702	U	J
11070	REPLACE HOT WATER STORAGE TANK	140703	U	J
11070	REPLACE HOT WATER STORAGE TANK	140703	U	J
11070	NO HOT WATER TO DISHWASHER	140703	U	J
10144	WATER TEMP DROPPING	140707	U	J
84201	WATER BREAK	140708	U	J
14400	WATER LEAK-WALL/FLOOR WET	140709	U	J
11070	NO HOT WATER TO DISHWASHER	140711	U	J
9190	BOTH SINKS/ WATER NOT RUNNING	140711	U	J
10130	DRINKING WATER FAUCET LEAKING	140711	U	J
84200	WATER SPILLING ON TO NEVADA	140714	U	J
84201	WATER LEAKS-POOLING AT GROUND	140714	U	J
14962	WATER LEAK AT SINK/UNDER SINK	140714	U	J
13121	WATER NOT HEATING IN BLDG	140715	U	J
10144	WATER TEMP TO HOT IN POOL	140715	U	J
13851	WATER LEAKING FROM CEILING	140716	U	J
1670	LOW WATER PRESSURE IN RESTRMS	140716	U	J
1335	WATER UNDER FLOOR	140717	U	J
8500	WATER FOUNTAIN LEAKS ON FLOOR	140718	U	J
11070	NO HOT WATER	140718	U	J
7025	NO CHILLED WATER	140722	U	J
13859	WATER HEATER HAS LEAK IN TANK	140722	U	J
10130	CEILING WATER LEAKS	140722	U	J
84101	WATER LEAKS QUITE A LOT GROUND	140722	U	J

84302	WATER LEAK BY EXT.FIRE HYDRONT	140722	U	J
9190	NO HOT WATER	140723	U	J
84201	WATER GUSHING FROM GROUND	140724	U	J
13857	NO HOT WATER TO BLDG 565 SIDE	140724	U	J
13857	REPAIR HOT WATER	140725	U	J
16177	NO WATER COMING OUT IN SINK	140725	U	J
10577	LEAKING WATER FOUNT LEAK	140728	U	J
8500	WATER LEAK FROM UTILITY FIXTUR	140729	U	J
10144	WATER LEAK - POOL	140729	U	J
875	**NO WATER IN BUILDING**	**140729**	**U**	**J**
84201	WATER BREAK	140730	U	J
13863	NO HOT WATER TO ROOMS	140902	U	J
10525	WATER COLLECTING/FLOOR DRAIN	140902	U	J
13852	WATER LEAK IN CEILING	140902	U	J
13330	NO HOT WATER	140902	U	J
8190	REPAIR HOT WATER	140902	U	J
840	HOT WATER PUMP/LOUD NOISE	140902	U	J
9192	URINAL LEAKING/ WATER ON FLOOR	140903	U	J
1546	WATER LEAKS	140908	U	J
11070	HOT WATER TOO HOT	140908	U	J
10577	REPAIR WATER DRAIN	140908	U	J
85170	WATER BREAK	140908	U	J
1846	WATER LINE TO TOILET	140909	U	J
7525	WATER LEAKING FROM CEILING	140911	U	J
11070	NO HOT WATER	140911	U	J
6710	WATER LEAKING FROM MECH ROOM	140912	U	J
84202	WATER PUDDLEING-LEAKING OUT	140915	U	J
1335	FAUCET WATER DIRTY BROWN COLOR	140930	U	J
22312	REPAIR FLASH WATER SYS/SCADA	141006	U	J
12315	WATER FOUNTAIN SPEWING WATER	141006	U	J
84101	REPAIR WATER MAIN BREAK	141006	U	J
11070	NO HOT WATER	141006	U	J
9360	WATER HEATER NOT OPERATING	141006	U	J
84101	REPAIR WATER MAIN BREAK	141007	U	J
730	ISOLATE MAIN WATER VALVE	141007	U	J
1610	WATER LINE LEAKING	141007	U	J
8305	WATER LINE LEAKING ON FLOOR	141008	U	J
16170	NO HOT WATER	141008	U	J
16170	WATER UP FROM FLOOR DRAIN	141008	U	J
856	NEED WATER & FUEL/POWER PRO	141009	U	J
8415	WATER FROM ROOF/ WATER BREAK	141014	U	J
11248	ELECTRIC WATER HEATER LEAKING	141015	U	J
2500	WATER YELLOWISH /BROWN	141015	U	J
13330	NO HOT WATER	141020	U	J
1508	SUPPLY WATER LEAK ON FILTER	141020	U	J
13864	WATER DRIPPIN FROM HEATER CORE	141021	U	J
1900	WATER FOUNTAIN LEAK	141022	U	J
10144	WATER TEMP TO COLD IN POOL	140919	U	J
14400	BROWN COLOR WATER COMING OUT	140922	U	J
23209	WATER HOSE RUNNING	140923	U	J
23209	WATER HOSE RUNNING	140923	U	J
12000	WATER LEAK	140925	U	J
12000	WATER LEAK	140925	U	J
1743	HVAC SYSTEM LEAKING WATER	140926	U	J
10130	HOT WATER HEATER LEAKING	140926	U	J
11152	NO DRINKABLE WATER	140926	U	J
84101	WATER BREAK	141124	U	J
13860	HOT WATER HEATER LEAKING	141124	U	J
84201	MULTIPLE WATER LINE BREAKS	141126	U	J
13864	NO HOT WATER	141201	U	J
84201	WATER LINE BREAK CONTRACTR HIT	141201	U	J
13123	RAIN WATER LEAKING THRU WALL	141202	U	J
16177	REPAIR WATER LEAK	141202	U	J
9192	SHOWER RUNS COLD WATER ONLY	141203	U	J
13022	REPLACE WATER MAIN VALVE	141203	U	J

8290	WATER LEAK/INTO LIGHT FIXTURE	141204	U	J
13135	WATER LEAK IN CEILING	141205	U	J
7025	BOILER MOTOR SPRAYING WATER	141208	U	J
84201	WATER LEAKING FROM PIPE	141208	U	J
84201	LOW WATER PRESSURE	141210	U	J
9192	SHOWERS RUNNING COLD WATER	141211	U	J
1705	HOLE IN PARK LOT/RUSHING WATER	141212	U	J
12000	WATER LEAKS ALOT INTO 2 ROOMS	141212	U	J
8500	WATER LEAKING ALOT INTO ROOM	141212	U	J
9192	RAIN WATER LEAKING INTO LOBBY	141212	U	J
6601	WATER LEAK/ INTO ELECTRICAL	141212	U	J
8175	WATER LEAK	141212	U	J
8312	CEILING WATER LEAK	141212	U	J
10363	REPAIR CLOGGED WATER DRAIN	141212	U	J
5500	3 WATER LEAKS IN BAY A	141212	U	J
8195	RAIN WATER LEAKING IN ROOM	141212	U	J
1559	REPAIR WATER LEAKS	141215	U	J
1559	REPAIR WATER LEAKS	141215	U	J
8305	NO COLD WATER COMING OUT-SINKS	141217	U	J
8500	WATER LEAKS AT FLOOR IN ROOM	141217	U	J
1546	WATER LEAK IN EXPLOSION RM	141218	U	J
11777	WATER LEAK ON ROOF	141022	U	J
84101	WATER BREAK	141022	U	J
13860	HOT WATER HEATER UNIT #6 LEAKS	141023	U	J
8173	WATER LEAKING AT CEILING	141023	U	J
1740	WATER LEAK	141024	U	J
13675	LEAKING WATER FOUNTAIN	141024	U	J
84201	POSSIBLE WATER BREAK	141027	U	J
84201	WATER LEAK COMING FROM GROUND	141027	U	J
12901	WATER LEAK	141029	U	J
84101	WATER BREAK	141029	U	J
8190	NO HOT WATER IN RESTROOM	141029	U	J
84101	WATER MAIN BREAK	141030	U	J
16170	WATER HEATER LEAKING	141031	U	J
13857	TOILET LEAKS WATER FROM BASE	141103	U	J
84201	SUPPORT EMERG WATER LINE BREAK	141104	U	J
16170	WATER LEAK	141104	U	J
10525	CHILLED WATER PUMP INOP	141104	U	J
1840	STANDING WATER IN SUBFLOOR	141105	U	J
10711	WATER MAIN VALVE LEAKING	141106	U	J
1521	WATER LEAK	141106	U	J
13860	BOILER LEAKING WATER	141107	U	J
490	TOILETS NOT FILLING UP/WATER	141107	U	J
10130	NO HOT WATER	141110	U	J
11777	WATER DRIPPING FROM CEILING	141110	U	J
5010	WATER LINE BREAK	141112	U	J
13858	WATER LEAK NEEDS REPAIRING	141112	U	J
1735	WATER PIPE LEAK	141113	U	J
13120	WATER LEAK/ FROM THE SINK	141114	U	J
73	INSPECT/REPAIR WATER LEAK	141114	U	J
7525	WATER LEAK PIPE BROKEN RM. 133	141117	U	J
11145	WATER LEAK	141118	U	J
7525	REPLAC MAIN WATER INLET MANIFL	141118	U	J
0	WATER WELL #7 WON'T START	141118	U	J
621	REPLACE WATER PUMPS	141118	U	J
13120	NO HOT WATER	141120	U	J
84101	WATER BREAK	141120	U	J
13858	WATER LEAK IN THE ROOM	141121	U	J
799	WATER LEAK UNDER SINK	141121	U	J
11070	RESERVE TANK LEAKING WATER	141218	U	J
11166	WATER LEAK IN BLDG	141218	U	J

499 rows selected.

Appendix I. Building Condition Index White Paper

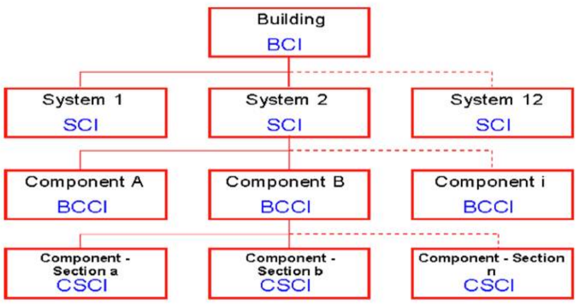
Aligning the Building Condition Index with Air Force Goals

The U.S. Army's Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) developed the BUILDER™ Sustainment Management System (SMS) as a facility and infrastructure asset management tool. In 2009, the Air Force Civil Engineering community began a process to integrate this tool into their asset management strategies and policies. The DoD then mandated the use of the BUILDER™ SMS software in a memorandum released in September 2013, which also sets a five-year deadline for having all facilities and components inspected and rated using BUILDER™. The desired end state for the community is an enterprise-wide asset management framework which can objectively assess an asset's condition state and lead to condition-based assessment decisions. BUILDER™ features the ability to produce condition-based assessments, but researchers at the Air Force Institute of Technology have discovered that these BUILDER™ assessments may not align with Air Force CE building system standards. This white paper outlines the current calculations used in the BUILDER™ system and proposes a new calculation in which results align with current Air Force CE building standards.

BUILDER™ Calculations

The BUILDER™ SMS uses a system of indices which roll-up into an overall building condition index (BCI) for a facility. Calculation of the BCI can be thought of as a four-tier hierarchy where the top level is the overall BCI. At the lowest level, individual building "component-sections" are evaluated, and their condition index and replacement values are collected. The component-section condition index (CSCI) level is the most detailed level and comprises subdivisions of each facility component. Subdivisions of a component are based on inventory decisions if parts of a component are dissimilar enough in structure, usage, location, age, or other attributes. The CSCI level forms the basis of data from which all other indices are calculated. Collecting an accurate inventory and the conditions for each item in the inventory is the most resource intensive step, but the most critical. Without this inventory and condition of assets, the fundamental approach behind the BUILDER™ SMS is undermined and calculation of an overall BCI is not possible.

Moving from the CSCI to the building component condition index (BCCI) requires the use of a weighted model where each section index is weighted by its replacement cost. Moving from BCCI to the system condition index (SCI) again employs a weighted model based on the previously calculated component index weighted by each components replacement cost. The final calculation of the BCI employs the same method using the previously calculated SCI and weights according to replacement cost. Figure 1 below illustrates the condition index hierarchy and the weighted models involved at each level of calculation.



$$BCI = \frac{\sum[SCI \times Individual\ System\ CRV]}{\sum Systems\ CRV}$$

$$SCI = \frac{\sum[BCCI \times Individual\ Component\ CRV]}{\sum Components\ CRV}$$

$$BCCI = \frac{\sum[CSCI \times Individual\ Component - Section\ CRV]}{\sum Component - Sections\ CRV}$$

Figure 1. Condition index hierarchy and weighted formulas. Adapted from Uzarski et al. (2007).

Moving from bottom to top in the hierarchy requires the weighted model calculations using condition index and replacement value. By defining each subsequent index in this way, replacement value of each unit (whether system, component, or component-section) imparts significant influence on the resulting index calculated for each level. This implies that systems or components which cost more are more important and therefore have a greater impact on the overall BCI.

A New BUILDER™ Calculation Model

The Air Force Civil Engineer Center (AFCEC) developed a set of standards at the system level that prescribes at what level repair or replacement is needed. The directive states (AFCEC, 2013) that there are three variables which would dictate what repairs and replacements are needed. The mission dependency index (MDI), condition index (CI), and remaining service life (RSL) comprise these indicators for building system repairs and replacements. This guidance provides a way for balancing mission needs with condition states for a building system. Logically, those components and component-sections that are most critical to building performance should be kept at a better condition state than those that are less critical to performance.

This logic leads to several implications. First, the AFCEC guidance provides for the MDI to influence CI standards. Since the MDI is a measure of importance to the mission, higher facility MDIs indicate a more important facility and therefore this facility and its systems must be kept at better condition states (i.e., higher CI standards). Second, the issue of undue influence (bias) from replacement values at the building system level is eliminated because these values are no longer required to determine relative importance for each system of the facility. Rather, a standardized direct weight is calculated based on current AFCEC guidance of CI standards and this weight is applied at the BCI level of calculation.

System	MDI									
	Critical 100-85		Significant 84-70		Relevant 69-55		Moderate 54-40		Low 39-0	
	CI	RSL	CI	RSL	CI	RSL	CI	RSL	CI	RSL
B20 Exterior Enclosure	88	2	88	2	71	1	71	1	60	0
B30 Roofing	88	2	88	2	71	1	71	1	60	0
C10 Interior Construction	71	1	50	0	50	0	50	0	50	0
C20 Staircases	71	1	50	0	50	0	50	0	50	0
C30 Interior Finishes	88	1	50	0	50	0	50	0	50	0
D20 Plumbing	88	2	71	1	50	0	50	0	50	0
D30 HVAC	88	2	71	1	71	1	50	0	50	0
D40 Fire Protection	88	2	71	1	71	1	50	0	50	0
D50 Electrical	88	2	88	2	71	1	71	1	60	0

Figure 2. Levels of standards at the section level. Released by AFCEC (2013).

In standardized direct weighting, an objective formula is created which incorporate criteria with relative importance. For this paper, the objective formula is the BCI calculation and relative importance are represented by standardized direct weights. To calculate these direct weights, the published CI standards provide the basis for the scores. A sample calculation and resulting weights are shown in Table 1, below.

Table 1. Sample calculation of standardized direct weights for “Significant” MDI.

	CI Standard	Calculation	Standardized
B20 Exterior Enclosure	88	88/627	14.0%
B30 Roofing	88	88/627	14.0%
C10 Interior Construction	50	50/627	8.0%
C20 Stairs	50	50/627	8.0%
C30 Interior Finishes	50	50/627	8.0%
D20 Plumbing	71	71/627	11.3%
D30 HVAC	71	71/627	11.3%
D40 Fire Protection	71	71/627	11.3%
D50 Electrical	88	88/627	14.0%
Sum	627		100.0%

With the calculation of the standardized weights for each system within a building, the BCI formula is transformed from a CRV-based formula to a standardized direct weighting formula. However, by using this direct weighting formula, the main problem that must be overcome is the difference in the MDI and CI scales. In the MDI scale, a facility that has a higher ranking is considered more important, and vice versa. Reversely, in the CI scale, a system that has a higher ranking is considered less important, as more importance should be placed on systems with low CI values. To overcome this difference, the inverse of the CI is taken by subtracting each of the SCI values from 100.

The new BCI model now aligns AFCEC desired system standards with calculated system level CI scores. Table 2 is illustrative of this point. Building 1228 from Eielson Air Force Base, AK was assessed by the AFCEC asset visibility team during the summer of 2013. The charts in Figure 3 illustrate the misalignment of priorities at the system level with the original formula and how the new system CI calculations realign these priorities.

Table 2. Building 1228 evaluation using new BCI calculation model

BLDG 1228 MDI = 70

ALTERNATIVES	B20 EXTERIOR ENCLOSURE	B30 ROOFING	C10 INTERIOR CONSTRUCTION	C20 STAIRS	C30 INTERIOR FINISHES
Standards	88	88	50	50	50
Weight	0.1404	0.1404	0.0797	0.0797	0.0797
System CI (SCI)	92	77	48	95	67
100 - SCI	8	23	52	5	33
CRV (System CRV / Building CRV)	0.10	0.03	0.00	0.00	0.52
Original BCI ∑(SCI * CRV)	9.57	2.29	0.20	0.35	35.09
New Relative BCI ∑[Weight * (100-SCI)]	1.12	3.23	4.14	0.40	2.63

ALTERNATIVES	D20 PLUMBING	D30 HVAC	D40 FIRE PROTECTION	D50 ELECTRICAL	BCI Total
Standards	71	71	71	88	
Weight	0.1132	0.1132	0.1132	0.1404	
System CI (SCI)	87	94	34	82	
100 - SCI	13	6	66	18	
CRV (System CRV / Building CRV)	0.00	0.13	0.04	0.15	
Original BCI ∑(SCI * CRV)	0.42	12.55	1.50	12.40	47
New Relative BCI ∑[Weight * (100-SCI)]	1.47	0.68	7.47	2.53	12
				100 - New Relative BCI =	88

System	SCI Std
B20 Exterior Enclosure	88
B30 Roofing	88
D50 Electrical	88
D20 Plumbing	71
D30 HVAC	71
D40 Fire Protection	71
C10 Interior Construction	50
C20 Stairs	50
C30 Interior Finishes	50

(a)

System	Orig. BCI Value	SCI
C30 Interior Finishes	35.1	67
D30 HVAC	12.5	94
D50 Electrical	12.4	82
B20 Exterior Enclosure	9.6	92
B30 Roofing	2.3	77
D40 Fire Protection	1.5	34
D20 Plumbing	0.4	87
C20 Stairs	0.3	95
C10 Interior Construction	0.2	48

(b)

System	New BCI Value	SCI
D40 Fire Protection	7.5	34
C10 Interior Construction	4.1	48
B30 Roofing	3.2	77
C30 Interior Finishes	2.6	67
D50 Electrical	2.5	82
D20 Plumbing	1.5	87
B20 Exterior Enclosure	1.1	92
D30 HVAC	0.7	94
C20 Stairs	0.4	95

(c)

Figure 3. Comparison of (a) AFCEC standards, (b) Original BCI calculations, and (c) New BCI calculations

Benefits of New BUILDER™ Calculation Model

The proposed model now provides the following benefits. First, a ranking is developed at the system level that better matches the MDI / CI standards outlined by the Air Force. In Figure 3b, the interior finishes system CI dominates the BCI calculation due to the high replacement value of this system. However, the Air Force views interior finishes as a lower priority system and the proposed BCI calculations reflect this priority. Second, the proposed model offers a framework for adjusting condition index calculations at other levels of the hierarchy. If the MDI / CI standards developed at the system level are translated to component ratings at the BCCI level, then rankings can be developed without reliance on CRV. One final benefit the model provides is the ability to rank work at the system level from individual buildings. This has implications to the work planning function of BUILDER™ in that a prioritized work plan can now be developed using the new BCI calculations rather than relying solely on a facility priority list or facilities MDI.

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Vita

Captain Stephanie Alley graduated from Immaculata High School in Leavenworth, Kansas. She was commissioned in 2010 with a Bachelor of Science degree in Architectural Engineering from the University of Kansas. After graduation, she was assigned to the 325th Civil Engineer Squadron at Tyndall Air Force Base, Florida. During her tenure, Captain Alley served as a Project Programmer and as the 325th Fighter Wing Executive Officer. During that assignment, she deployed in 2011 for six months to Afghanistan to serve as the Engineering Flight Chief for the 838th Air Expeditionary Advisory Group, J7, stationed at Shindand Air Base. Capt Alley entered the Air Force Institute of Technology at Wright-Patterson Air Force Base, Ohio in August 2013. Upon graduation in March 2015, she will be assigned to the 4th Civil Engineer Squadron at Seymour Johnson Air Force Base, North Carolina.

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14. ABSTRACT
Deteriorating and failing federal facilities represent a cost to leaders and organizations as they attempt to manage and maintain these assets. Currently the Air Force employs the BUILDER™ Sustainment Management System to predict the reliability of building components. At different system levels, however, the probabilities of failure are not predicted. The purpose of this research is to provide probabilistic models which predict the probability of failure at the system level of a building's infrastructure hierarchy. This research investigated the plumbing, HVAC, fire protection, and electrical systems. Probabilistic models were created for these systems by using fault trees with fuzzy logic on the basis of risk by weighting the probabilities of failure by the consequences of failure. This thesis then validated each of the models using real-world Air Force work order data. Through contingency analysis, it was found that the current BUILDER™ condition index model possessed no predictive ability due to the resulting p-value of 1.00; the probabilistic models possessed much more predictive ability with a resulting p-value of 0.12. The probabilistic models are statistically shown to be a significant improvement over the current condition index model; these models lead to improved decision making for infrastructure assets.

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